IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

| | | |
|---|---|---|
| In re: | Application of Gruenwald, et al. | Attorney's Docket: 104035-00010 |
| Serial No.: | 10/721,000 | |
| Filed: | 11/24/03 | Examiner: Basil Kalcheves |
| Title: | HYBRID ELECTRIC VEHICLE | Group Art Unit 3635 |

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Sheri L Burke
Sheri L. Burke

**VERIFIED STATEMENT (DECLARATION) OF JEFF MAJOR UNDER 37 C.F.R. §1.131**

I, Jeff Major, hereby declare that I am over 21 years of age, of sound mind, capable of making this declaration, and fully competent to testify concerning the matters stated herein. I have personal knowledge of each of the matters stated herein.

I am one of the co-inventors of the inventions described and claimed in the above-referenced patent application.

I understand that the United States Patent and Trademark Office has rejected claims in the above-referenced application as either anticipated by the Morisawa et al. reference (US Patent No. 6,205,379), or obvious in view of that reference in combination with other references, as set forth in the Official Action mailed February 11, 2005, the Morisawa et al. reference cited under 35 USC 102(e) as having been based upon an application filed August 12, 1999.

I also understand that the United States Patent and Trademark Office has rejected claim 30 in the above-referenced application as obvious in view of the Morisawa et al. reference (US Patent No. 6,205,379) in combination with the teaching of the Deguchi et al. reference (US Patent No. 6,233,508), as set forth in the Official Action mailed February 11, 2005, the Deguchi et al. reference cited under 35 USC 102(e) as having been based upon an application filed June 3, 1999.

The inventions of the present patent application were completed and reduced to practice at least as early as the June 3, 1999 filing date of the Deguchi et al. reference, and prior to the August 12, 1999 filing date of the Morisawa et al. reference.

Attached hereto as Exhibits A is a true and accurate copy of a confidential memorandum authored by Mr. Robert Gruenwald, co-inventor of the subject application, and describing the hybrid vehicle software whose operation is described and claimed in the subject application and developed by the inventors named in the subject application. The memorandum bears a latest revision date of November January 27, 1998. Exhibit A describes the program parameters of the software described in the subject application, including the setting of an "Undervoltage Max" and an "Undervoltage Min" that refers to the setting of a pre-determined low voltage set-point for the energy storage

system; and the setting of an "Overvoltage Max" and an "Overvoltage Min" that refers to the setting of a pre-determined high voltage set-point for the energy storage system.

Also attached hereto as Exhibits B is a true and accurate of a document entitled "Baseline Testing of the Hybrid Electric Transit Bus" that describes the testing of a hybrid bus of the type that embodied the inventions described and claimed in the subject application. Figures 1 and 2 of that document show pictures of the hybrid electric bus that incorporated the inventions described and claimed in the subject application, including the software described in Exhibit A.

Accordingly, I confirm of my own knowledge that the subject invention was completed and in operation, as reflected in the aforementioned exhibits, at least as early as June 3, 1999.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that the statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 10001 of Title 18 of the United States Code, and that such willful false statements made jeopardize the validity of the application, any patent issuing thereon, or any patent to which this verified statement is directed.

Jeff T. Major

Jeff T. Major

August 10, 2005

Date of Execution

# EV Software

Document Name: IM114213.doc
Document Revised: 01/27/98
Software number: 114213
Software Revised: 06/13/97

This software was created to allow EMS G5 drive control and electric vehicle. The special features of the software include:

1. Gas and brake peddle analog inputs.
2. Under voltage trip prevention
3. Over voltage trip prevention.
4. Power level selection.
5. Regeneration speed cut off.
6. Shift control of two-speed transmission.

## ***Block diagram of torque control***

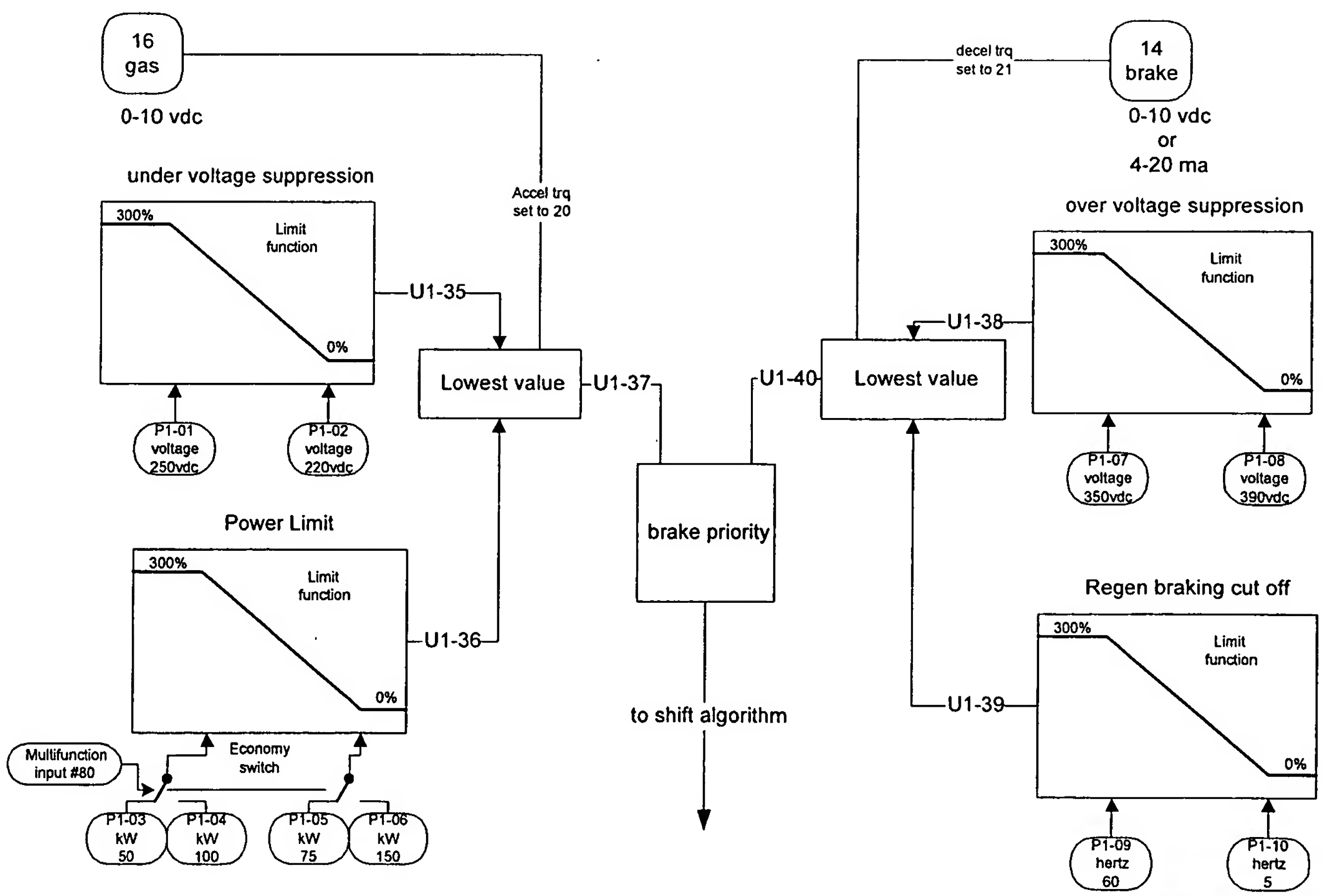
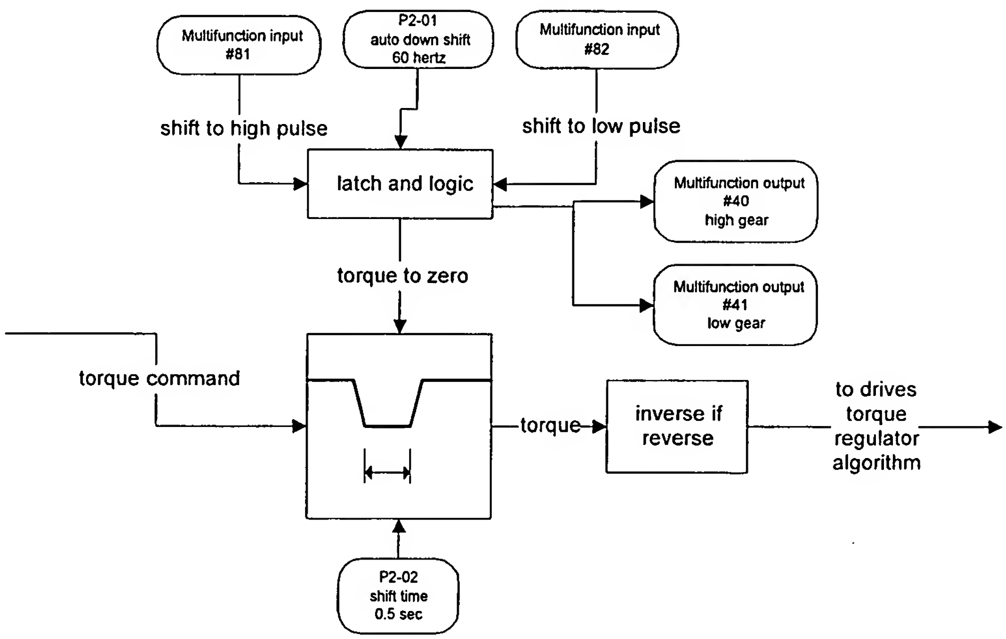


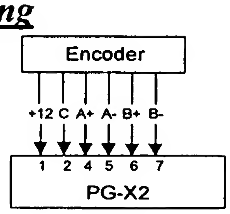



EXHIBIT
A

# *Block diagram of shift control*




## *Encoder Wiring*



Special Programming Notes
This software document is only a supplement to the EMS G5 Series instruction manual. All parameters and features not mentioned in this document are not changed. A **PG-W2** or **PG-X2** card must be used as pulse feedback card. The drive must operate in closed loop Flux vector mode.

**Factory defaults that are changed.**

| | |
|---|---|
| A1-01 = 4 | Advanced access level |
| A1-02 = 3 | Vector Control |
| B1-01 = 0 | Reference from operator |
| B1-03 = 1 | Coast to stop control |
| B1-06 = 0 | 2ms Scan time for inputs |
| C1-01 = 0.5 | Acceleration |
| C1-02 = 0.5 | Deceleration |
| C2-01 = 0 | S-curve at acceleration start |
| C2-02 = 0 | S-curve at acceleration end |
| C2-03 = 0 | S-curve at deceleration start |
| C2-03 = 0 | S curve at start of deceleration |
| C4-01 = 0 | Torque compensation gain |
| C6-01 = 12.0 | Carrier Frequency |
| C6-01 = 12.0 | Carrier Frequency |
| D1-01 = 60.00 | frequency reference #1 |
| D5-01 = 1 | torque control |
| D5-02 = 5 | Torque ref filter |
| E1-02 = 1 | Blower cooled motor |
| E1-13 = 230.0 | base voltage |
| F1-01 = 512 | Encoder PPR |
| H1-03 = 80 | terminal 5 is economy mode command input |
| H1-04 = 81 | terminal 6 shift to high gear input |
| H1-05 = 82 | terminal 7 shift to low gear input |
| H2-02 = 41 | terminal 25 is shift to high output |
| H2-03 = 40 | terminal 26 is shift to low output |
| H3-01 = 1 | terminal 13is a bipolar input |
| H3-05 = 20 | terminal 16 is gas pedal input |
| H3-06 = 300.0 | terminal 16 gain |
| H3-08 = 0 | terminal 14 is 0 to 10v |
| H3-09 = 21 | terminal 14 is brake pedal input |
| H3-10 = 300.0 | terminal 14 gain |
| L2-05 = 150 | Under voltage detection level |
| L3-04 = 0 | Disable stall prevention |
| L7-01 = 300 | Forward torque limit |
| L7-02 = 300 | Reverse torque limit |
| L7-03 = 300 | Forward regeneration torque limit |
| L7-04 = 300 | Reverse regeneration torque limit |
| O1-01 = 7 | User monitor dc bus voltage |
| O1-02 = 4 | User monitor at power up |

**Additional changes for Bob's minivan.**

| | |
|---|---|
| B1-02 = 0 | keypad run command |
| D1-01 = 166.00 | frequency reference #1 |
| E1-04 = 166.00 | Max frequency |
| E1-06 = 100 | Fbase |
| E2-01 = 100 | FLA |
| E2-02 = 0.47 | Slip |
| E2-03 = 55.6 | NLA |
| E2-05 = 0.034 | terminal resistance |
| E2-07 = 0.39 | Saturation |
| E2-08 = 0.60 | Saturation |

# *Custom software Parameters*

Q: Quick-Start Level, selected parameters for maintenance-level programming.
B: Basic Level, selected parameters for basic programming in most applications.
A: Advanced Level, all parameters for advanced programming in special applications.

## *New Multi-Function Digital Input Setting*

For Constants H1-01 through H1-06

| Setting | Display | Description |
|---|---|---|
| 80 | Economy Mode | Closing this input causes the drive to use P1-03 and P1-04 Power limits. |
| 81 | Shift to high. | Closing this input causes the drive to change the transmission to high gear. |
| 82 | Shift to low. | Closing this input causes the drive to change the transmission to low gear. |

## *New Multi-Function Digital Output Setting*

For Constants F5-01 & 02 and H2-01 through H2-03

| Setting | Display | Description |
|---|---|---|
| 40 | High Gear | Output to transmission high gear. |
| 41 | Low Gear | Output to transmission low gear. |

## *New Multi-Function Analog Input Setting*

For Constants H3-05 and H3-09

| Setting | Display | Description |
|---|---|---|
| 20 | Gas Pedal input | Analog input from gas pedal |
| 21 | Brake Pedal input | Analog input from brake pedal |

## *New Multi-Function Analog Output Setting*

For Constants H4-01 and H4-04

| Setting | Display | Description |
|---|---|---|
| none | | |

*New Program Group*

Group P
Electric Vehicle

*New Program Function*

Function P1
EV Torque Contr

*New Program Parameters*

Undervoltage Max
P1-01= 250 VDC

***P1-01 Under Voltage Maximum***

| - | - | - | B |
|---|---|---|---|

Setting Range: 0 to 999 VDC
Factory Default: 250 VDC

When DC bus voltage is above this point 300 percent acceleration torque is possible.

Undervoltage Min
P1-02= 220 VDC

***P1-02 Under Voltage Minimum***

| - | - | - | B |
|---|---|---|---|

Setting Range: 0 to 999 VDC
Factory Default: 220 VDC

When DC bus voltage is below this point zero percent acceleration torque is possible.

Pwr.Lim.Econ.Max
P1-03= 50 kW

***P1-03 Power Limit Economy mode maximum***

| - | - | - | B |
|---|---|---|---|

Setting Range: 0 to 999 kW

Factory Default: 50 kW

When in economy mode and power output is below this point 300 percent acceleration torque is possible.

| Pwr.Lim.Perf.Max |
|---|
| P1-04= 100 kW |

***P1-04 Power Limit Performance mod maximum***

| - | - | - | B |
|---|---|---|---|

Setting Range: 0 to 999 kW
Factory Default: 100 kW

When in performance mode and power output is below this point 300 percent acceleration torque is possible.

| Pwr.Lim.Econ.Min |
|---|
| P1-05= 75 kW |

***P1-05 Power Limit Economy mode minimum***

| - | - | - | B |
|---|---|---|---|

Setting Range: 0 to 999 kW
Factory Default: 75 kW

When in economy mode and power output is above this value, zero percent acceleration torque is possible.

| Pwr.Lim.Perf.Min |
|---|
| P1-06 = 150 kW |

***P1-06 Power Limit Performance mod minimum***

| - | - | - | B |
|---|---|---|---|

Setting Range: 0 to 999 kW
Factory Default: 150 kW

When in performance mode and power output is above this value zero percent acceleration torque is possible.

| Overvoltage Max |
|---|
| P1-07= 350 VDC |

***P1-07 Overvoltage maximum***

| - | - | - | B |
|---|---|---|---|

Setting Range: 0 to 999 VDC
Factory Default: 350 VDC

When DC bus voltage is below this point 300 percent acceleration torque is possible.

| |
|---|
| Overvoltage Min |
| P1-08= 390 VDC |

***P1-08 Overvoltage minimum***

| - | - | - | B |
|---|---|---|---|

Setting Range: 0 to 999 VDC
Factory Default: 390 VDC

When DC bus voltage is above this point zero percent acceleration torque is possible.

| |
|---|
| Regen off Max |
| P1-09= 60 HZ |

***P1-09 Regeneration off maximum***

| - | - | - | B |
|---|---|---|---|

Setting Range: 0 to 999 HZ
Factory Default: 60 HZ

When motor speed is above this point 300 percent regeneration torque is possible.

| |
|---|
| Regen off Min |
| P1-10= 5 HZ |

***P1-10 Regeneration off minimum***

| - | - | - | B |
|---|---|---|---|

Setting Range: 0 to 999 HZ
Factory Default: 5 HZ

When motor speed is below this point zero percent regeneration torque is possible.

***<u>New Program Function</u>***

| |
|---|
| Function P2 |
| EV Shift Control |

## *New Program Parameters*

| Auto Down Shift<br>P2-01= 60 HZ |
|---|

***P2-01 Auto Down shift speed***

| - | - | - | B |
|---|---|---|---|

Setting Range: 0 to 999 HZ
Factory Default: 60 HZ

When the motor speed goes below this speed it automatically shift the transmission to low gear.

| Shift Time<br>P2-02= 500 ms |
|---|

***P2-02 Shift Time***

| - | - | - | B |
|---|---|---|---|

Setting Range: 0 to 9999 ms
Factory Default: 500 ms

When the shifting gears the torque on the motor is held at zero percent for this time to allow the transmission to change gears.

| Term-13 amp/volt<br>P2-03= 37.5 |
|---|

***P2-03 Terminal 13 amp per volt ratio***

| - | - | - | B |
|---|---|---|---|

Setting Range: 0.0 to 999.9
Factory Default: 37.5

This setting is used to calibrate the current transformer connected to terminal 13. The current transformer is used to measure DC bus amperage and calculate kWh used.

## *New Monitors*

| UV Suppress TRQ<br>U1-35 300.0 % |
|---|

*U1-35 Under Voltage Suppression torque.*
Displays the value of torque coming out of the under voltage suppression algorithm.
Range: 0 to 300.0 %

```
Power limit TRQ
U1-36   300.0 %
```

*U1-36 Power limit Torque*
Displays the value of torque coming out of the power limit algorithm.
Range: 0 to 300.0 %

```
Acceleration TRQ
U1-37    75.0%
```

*U1-37 Acceleration Torque*
Displays the lowest value of torque coming out of the under voltage suppression, gas pedal, or power limit algorithm.
Range: 0 to 300.0 %

```
OV Suppress TRQ
U1-38   300.0 %
```

*U1-38 Over Voltage Suppression torque.*
Displays the value of torque coming out of the over voltage suppression algorithm.
Range: 0 to 300.0 %

```
Regen Cutoff TRQ
U1-39   300.0 %
```

*U1-39 Regeneration cut off torque*
Displays the value of torque coming out of the regeneration cutoff algorithm.
Range: 0 to 300.0 %

| Deceleration TRQ |
| --- |
| U1-40 0.0% |

*U1-40 Deceleration Torque*
Displays the lowest value of torque coming out of the over voltage suppression, brake pedal, or regeneration cutoff algorithm.
Range: 0 to 300.0 %

| Torque Reference |
| --- |
| U1-41 75.0% |

*U1-41 Torque Reference*
Displays the torque reference sent to the shift algorithm.
Range: 0 to 300.0 %

| DC Bus Amps |
| --- |
| U1-42 20.4 A |

*U1-42 DC Bus Amps*
Displays the amperage of the DC bus measured by the current transformer connected to terminal 13.
Range: -1000.0 to 1000.0 Amps

| kWh Used |
| --- |
| U1-43 21.340 |

*U1-43 Kilowatt-hour used.*
Displays the kilowatt-hour used since power was applied to the inverter. It uses dc bus voltage and the CT connected to terminal 13 to calculate this value.
Range: -9.999 to 99.999 kWh

## *New Fault Codes*

| Fault Display | Name | Description | Corrective action | Class |
|---|---|---|---|---|
| none | | | | |

NASA/TM—1999-208890

# Baseline Testing of the Hybrid Electric Transit Bus

Jeffrey C. Brown, Dennis J. Eichenberg, and William K. Thompson
Lewis Research Center, Cleveland, Ohio

January 1999

EXHIBIT

B

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NASA/TM—1999-208890

# Baseline Testing of the Hybrid Electric Transit Bus

Jeffrey C. Brown, Dennis J. Eichenberg, and William K. Thompson
Lewis Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Lewis Research Center

January 1999

## Acknowledgments

The authors wish to acknowledge and thank all members of the Hybrid Electric Transit Bus team who have been a key the success of this project. This includes the following organizations:

Bowling Green State University
Greater Cleveland Regional Transit Authority
Howard University
Lincoln Electric Motor Division
NASA Lewis Research Center
Ohio Department of Development
National Highway Traffic Safety Administration Vehicle Research and Test Center
Transportation Research Center, Inc.





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# BASELINE TESTING OF THE HYBRID ELECTRIC TRANSIT BUS

Jeffrey C. Brown, Dennis J. Eichenberg, and William K. Thompson
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

## SUMMARY

A government, industry and academic cooperative is developing an advanced hybrid electric city transit bus. Goals of this effort include doubling the fuel economy of buses currently in service and reducing emissions to one tenth of EPA standards. Unique aspects of the vehicle's power system include the use of ultra-capacitors for the energy storage system, and the planned use of a natural gas-fueled turbogenerator, developed from a small jet engine. At over 17000 kg gross weight, this is the largest vehicle to ever use ultra-capacitor energy storage. Power from both the auxiliary power unit and the energy storage system is delivered to a variable speed electric motor that drives the rear axle.

The bus uses regenerative braking to improve fuel efficiency. This technology recovers much of the kinetic energy of the vehicle during deceleration. This replenishes the energy storage system each braking cycle and extends the life of the mechanical brakes.

The bus was tested at the Transportation Research Center in East Liberty, Ohio between September 21-25, 1998. Tests were performed to characterize the vehicle's performance using industry standard drive cycles. This paper describes the HETB vehicle, the results of performance tests, and future plans for vehicle development.

## INTRODUCTION

The NASA Lewis Research Center initiated the Hybrid Electric Transit Bus project as an excellent opportunity to transfer technology from the aerospace and military industries to a commercial venture. The project is seen as a way to reduce pollution in urban areas, reduce fossil fuel consumption and reduce operating costs for mass transit systems.

The NASA Lewis Research Center provides overall project coordination, expertise in system modeling and experience selecting key components. NASA Lewis is responsible for developing the vehicle power control system. This includes charge and discharge circuitry for the energy storage system and control algorithms. Wherever practical, off-the-shelf components have been integrated into the power control system.

The Greater Cleveland Regional Transit Authority (RTA) is a large urban transit authority that operates over 700 buses in greater Cleveland. RTA is a good example of a potential customer. It is located near the other partners and has aggressively pursued new technologies to reduce emissions. RTA has developed the infrastructure to support alternative fuels, especially natural gas. RTA supplied the project with a vehicle and has supported the subsequent modifications and testing.

Bowling Green State University (BGSU), College of Technology, is a leader in the development of electric vehicle drive trains. BGSU and the Lincoln Electric, Inc., Motors Division, developed the traction and auxiliary motors. BGSU engineered and assembled the major drive train components onto the rear engine cradle of the bus.

Howard University (Washington, DC) is responsible for developing advanced energy management algorithms using neural network technology. This may eventually offer more fuel-efficient operation of hybrid vehicles by adjusting the state of the energy system based on the recognition of variable route conditions. The project team plans to incorporate these algorithms into the vehicle controller at a later date.

Flxible, Inc., has historically been the dominant producer of forty-foot transit buses. This duty class of urban transit buses is the mainstay of the industry. Flxible became a market leader by producing an advanced semi-monocoque aluminum-bodied vehicle at the lowest cost. Although the forty-foot Flxible bus is currently out of production, Flxible supported the vehicle engineering and integration. Since Flxible is no longer producing buses, the project is seeking other vehicle manufacturers to embrace the technology and either manufacture hybrids or retrofit conventional vehicles to a hybrid configuration.

## TEST OBJECTIVES

The Department of Transportation's Transit Bus "White Book" was used as a basis for the hybrid electric transit bus testing that was performed at the Transportation Research Center. Of particular interest are the following characteristics: fuel economy, vehicle speed, acceleration time, average acceleration, maximum jerk, gradeability, sound level, range over stop-and-go driving schedules, and regenerative braking results. The performance of the various vehicle components, especially the motors, controllers, auxiliary power unit (APU), and energy storage system are also of interest.

## TEST VEHICLE DESCRIPTION

The Hybrid Electric Transit Bus (HETB) is a converted forty-foot Flxible transit bus. The vehicle is shown in Figs. 1 and 2 and described in detail in Appendix A. The HETB is a series-hybrid as shown in Fig. 3. Series-hybrids convert all power produced by the generator to electric power. The combination of electric power from the engine-generator and the energy storage system power the single centrally located variable-speed electric motor that is attached to the rear differential/axle. The engine-generator and energy storage systems power all of the auxiliary systems of the bus as well. These include lighting, heating, pneumatics, hydraulics, and other vehicle systems. The engine-generator combination is also referred to as the auxiliary power unit (APU).

The energy storage system uses a 2100 lb. bank of thirty ultra-capacitors to store electrical energy. The capacitor bank is shown in Fig. 4. The capacitor bank is capable of storing 1.6 MJ of energy (20 Farads at 400 Volts). This state-of-the-art technology not only has much longer life than conventional batteries, but also provides exceptional capability to recover energy that would otherwise be lost during braking. The HETB is the largest vehicle ever to use ultra-capacitor energy storage.

Fig. 1 – Hybrid Electric Transit Bus

NASA
C-98-1482


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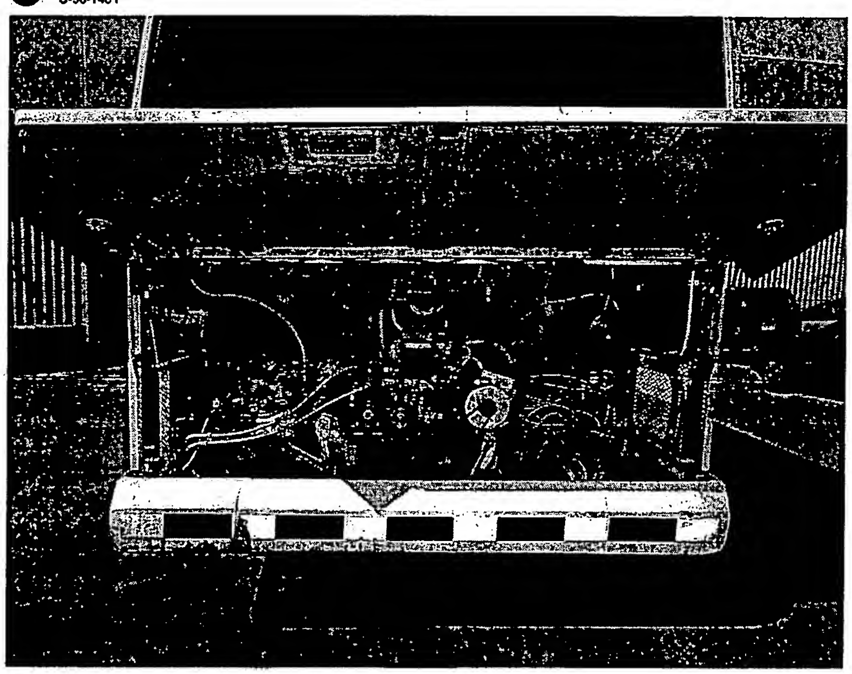
Fig. 2 – HETB Rear Cradle

NASA
C-98-1481



National Aeronautics and Space Administration
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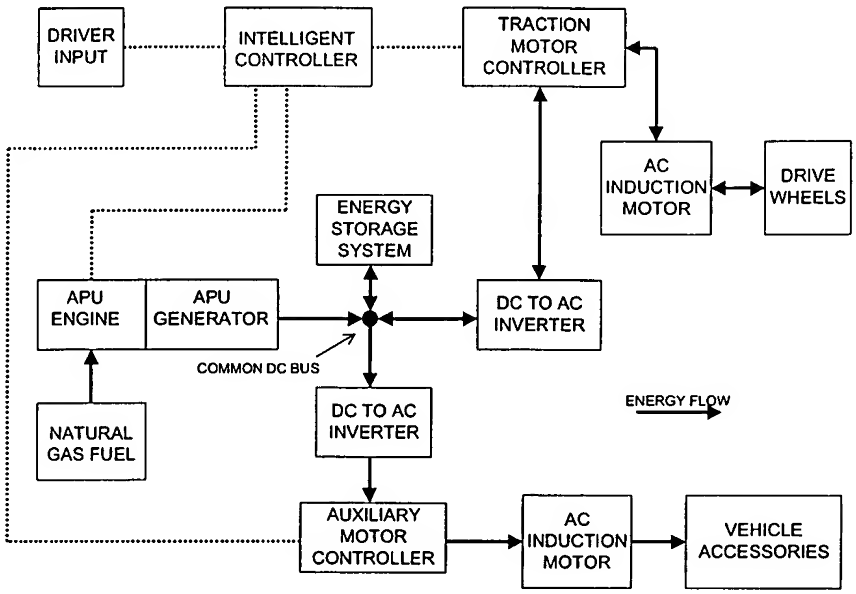
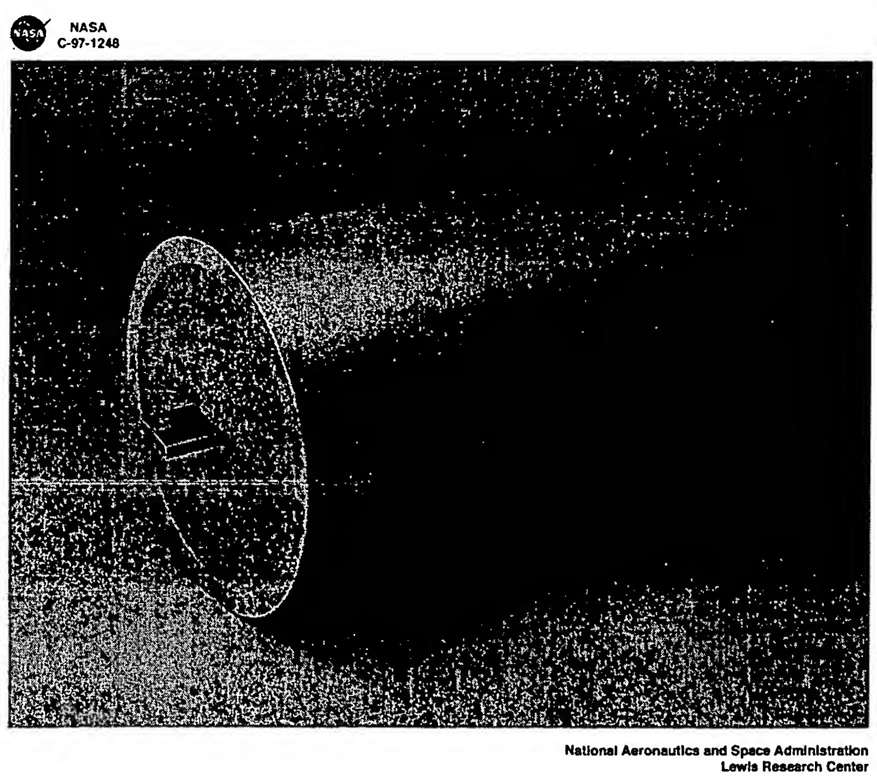
Fig. 3 – HETB Schematic Diagram




**SERIES HYBRID SCHEMATIC**

Fig. 4 – Ultra-Capacitor



The electric traction motor is a four-quadrant, vector-controlled AC induction motor. Induction motors are very reliable. Vector motor controllers allow for independent and efficient torque control over a wide speed range. This Lincoln Electric motor is designed with a light alloy frame. BGSU-designed the motor's oil cooling system. The motor produces 200 HP but weighs only 350 lb. An auxiliary motor drives the other subsystem loads, such as air and hydraulic pumps.

The power management and data acquisition system consists of a programmable logic controller (PLC), a laptop computer and a communication bus. The PLC sequences the various subsystems at startup and shutdown. The laptop computer controls the operation of the APU in response to the state of discharge of the energy storage system. The laptop PC also acts as an operator interface. Optimizing the state of the energy storage system during the driving cycle allows for full recovery of energy during braking. This enhances vehicle performance. The response to the driver's acceleration and brake controls is similar to a conventional vehicle.

For these tests, the vehicle's APU is rated at 50 kW over a voltage range of 250 V to 360 V. The engine is a 5-cylinder inline, 2.3-liter displacement. It was modified to run on compressed natural gas (CNG). The generator is a 12-pole, wound field machine with 3-phase rectified output. It delivers rated voltage over a speed range of 2100 to 6000 rpm.

The APU controller receives a power setpoint command from the laptop computer. It then determines the optimum engine speed for that power level and moves the engine to that speed. The speed/load curve is programmed into the APU controller to produce power at the point of lowest emissions and greatest fuel economy. The APU controller will shut the APU down under certain fault conditions, such as low oil pressure, high coolant temperature, engine over-speed and high/low voltage.

The choice of the energy storage system and its electrical characteristics strongly influences the control strategy used. Ultra capacitors have several properties that are significantly different from the chemical batteries typically used on electric vehicles.

First, the state of charge of the capacitors may be very accurately determined from the measured terminal voltage. This is a significant advantage over batteries, whose relationship between state of charge and terminal voltage is highly non-linear. Batteries also exhibit hysteresis in their voltage, current and state of charge relationships. Batteries, therefore, require a much more sophisticated control system to manage state of charge.

Another difference between batteries and capacitors is that batteries must be current limited and/or cell voltage limited. This is especially true during the charging cycle, and it becomes critical as the battery approaches a full charge. Near full charge, lead acid and many other chemical batteries cannot accept high currents without plate damage. To prevent loss of battery life, additional controls are required. This further complicates the control system. On the other hand, capacitors can accept very high currents. They approach their voltage limit more slowly and do not experience damage while accepting currents just below full charge.

Batteries do have a much greater energy storage capacity than capacitors. Although the capacitor bank on the HETB is quite large, much of its energy is consumed during a single sustained acceleration.

In order to compare the performance of these two energy storage options, the HETB was temporarily equipped with two series strings of twenty-eight 12 V batteries. These batteries are Optima D750S, 12 V, 50 A-hr deep cycle units. These are sealed, maintenance-free, absorbed glass mat batteries, representing the state-of-the-art in lead acid battery technology.

When the capacitors are used for energy storage, the laptop computer executes a proportional-integral (PI) control algorithm to maintain the capacitor voltage as close as possible to a predetermined setpoint (325-350 V). This is accomplished by varying the power requested from the APU. The control algorithm is described in detail in Appendix F. When batteries are used, an operator manually controls the power requested to the APU from the laptop in order to keep the battery voltage near a setpoint of 336 V.

## INSTRUMENTATION

The HETB was instrumented to measure vehicle speed, distance, acceleration, jerk and sound pressure levels. Additional channels measured the APU voltage, as well as the following currents: traction motor, auxiliary motor, energy storage system and generator. Temperatures were measured at the APU, the ultra-capacitors, the rear cradle, traction motor stator, traction motor controller, auxiliary motor stator and the outside ambient temperature. Most of these data were sent to an on-board digital data acquisition system, sampled at 100 Hz and recorded on digital tape. The APU voltage was sampled at 1 Hz and stored on the laptop PC, which was externally synchronized with the data acquisition system. The instrumentation configuration is described in Appendix B.

Power for the data acquisition system, was derived from the vehicle's 12 V starting, lighting and ignition (SLI) battery.

The fuel economy tests were conducted using a small auxiliary tank that was filled with CNG prior to the test. The tank was initially weighed and then installed. Following the test, the tank was weighed again to determine fuel consumption.

## TEST PROCEDURES

The tests described in this report were conducted at the Transportation Research Center in East Liberty, Ohio. A description of the track is given in Appendix C. The tests were conducted in accordance with the White Book Technical Specifications for Wheelchair-Accessible 40-Foot Transit Coaches, provided in Appendix D.

## TEST RESULTS

### Vehicle Performance

Eleven tests were conducted to determine vehicle performance, per Table 1:

**Table 1 – Performance Tests Conducted on the Hybrid Electric Transit Bus**

| *Test Number* | *Energy Storage System Used* | *Regenerative Braking Used?* | *Top Vehicle Speed* | *Driving Cycle* |
|---|---|---|---|---|
| 1 | Capacitors | No | 15 mph | 7 CBD cycles, Fuel Economy |
| 2 | Capacitors | Yes | 15 mph | 7 CBD cycles, Fuel Economy |
| 3 | Capacitors | No | 15 mph | 2 CBD cycles |
| 4 | Capacitors | Yes | 15 mph | 2 CBD cycles |
| 5 | Batteries | No | 15 mph | 2 CBD cycles |
| 6 | Batteries | Yes | 15 mph | 2 CBD cycles |
| 7 | Batteries | No | 20 mph | 2 CBD cycles |
| 8 | Batteries | Yes | 20 mph | 2 CBD cycles |
| 9 | Batteries | No | 35 mph | 2 Arterial cycles |
| 10 | Batteries | Yes | 35 mph | 2 Arterial cycles |
| 11 | Batteries | No | 35 mph | Acceleration test to 35 mph |

A similar set of plots have been included in Appendix E for each of the tests:

a. Vehicle Speed, system voltage,and component currents vs. elapsed time
b. Vehicle Speed, system voltage,and component powers vs. elapsed time
c. Component temperatures vs. elapsed time
d. Vehicle Speed and accleration vs. elapsed time
e. Vehicle Speed, APU power requested, APU power delivered and APU engine speed vs. elapsed time

A summary of the test results is shown in Table 2 at the end of this section.

During the test period the winds were light. There were no indications that the winds affected the test results.

### Maximum Speed

The maximum speed of the vehicle was measured to be 40 mph in first gear during the preliminary checkout. The maximum speed is defined as the average speed that could be maintained on the track under full power. No maximum speed measurement was made in second gear.

## Fuel Economy

The fuel economy of the vehicle was determined from the following information:

*Air density = 0.0807 lb/scf*
*Air density relative to fuel = 0.578*
*Diesel fuel equivalent: 100 scf of CNG = 0.748 gal diesel*

$$MPG_{diesel} = \frac{miles}{lb\_CNG\_used} \times \frac{0.0807lb}{scf\_air} \times \frac{0.578scf\_air}{scf\_CNG} \times \frac{100scf\_CNG}{0.748gal\_diesel}$$

Capacitors were used as the energy storage system for the fuel economy tests. Two fuel economy tests were conducted, one with regenerative braking and one without. The CBD driving cycle was used over a four-mile route (28 cycles).

The results of the two fuel economy tests were 3.01 mpg with no regenerative braking and 3.65 mpg with regenerative braking. This translates to an improvement of 21.2% with the use of regenerative braking. These results are compared with a typical diesel vehicle in Fig. 5.

## Acceleration

The average acceleration, $a_n$, of the vehicle is computed as a change in vehicle speed as a function of time.

$$a_n = \frac{v_n - v_{n-1}}{t_n - t_{n-1}}$$

Acceleration times are given in Table 2. As shown in Fig. 6, the HETB traction control system is capable of meeting the White Book acceleration specification up to 35 mph in first gear. This particular test was conducted using the batteries.

## Gradeability

The maximum specific grade, in percent, that a vehicle can climb at a particular speed, *v*, was determined from maximum acceleration tests using the equation:

$$G = 100 \tan (\sin^{-1} 0.0455\, a_n)$$

for *v* mph.

Fig. 5

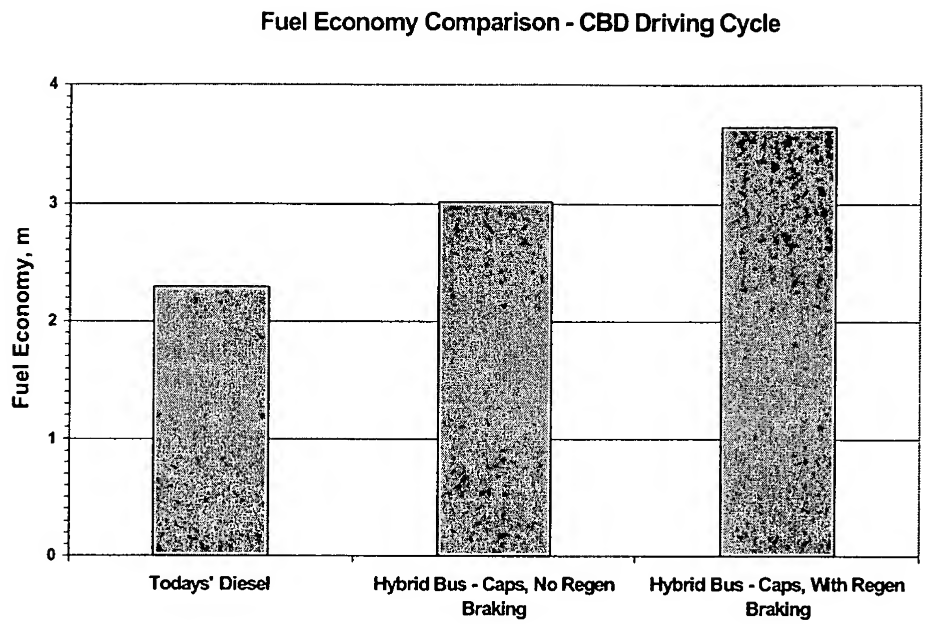
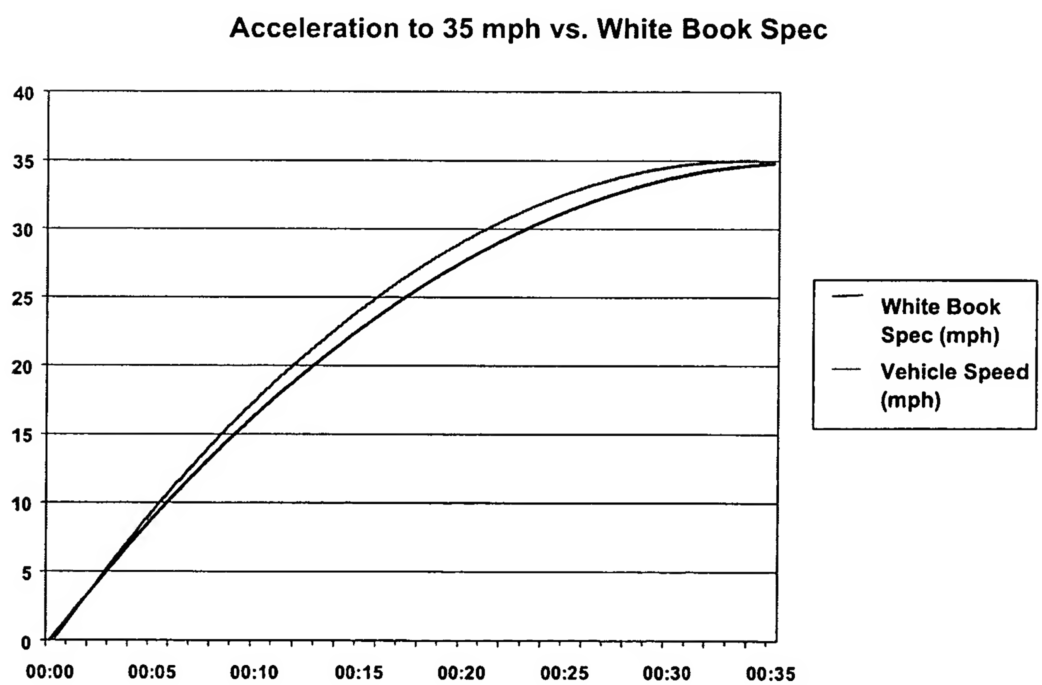

Fuel Economy Comparison - CBD Driving Cycle
Fuel Economy, m
0
1
2
3
4
Todays' Diesel
Hybrid Bus - Caps, No Regen Braking
Hybrid Bus - Caps, With Regen Braking

Fig. 6


Acceleration to 35 mph vs. White Book Spec
40
35
30
25
20
15
10
5
0
00:00
00:05
00:10
00:15
00:20
00:25
00:30
00:35
White Book Spec (mph)
Vehicle Speed (mph)

## Sound Pressure Level

The sound pressure level of the vehicle was monitored inside the vehicle. The sensor was positioned behind the driver at ear level, or 45 inches above the floor. For a one-mile (7-cycle) CBD test with capacitor energy storage and regenerative braking, the maximum sound pressure level was 73 dBA and the average sound level was 40 dBA., as shown in Fig. 7. The sound level is highest during and just after acceleration, when the APU and drive train are providing maximum power output. The sound level is much lower when the vehicle is idle.

## Range

The range of the vehicle was determined from the fuel economy data. The vehicle has three CNG fuel tanks. Each tank holds 2683 scf of CNG at 3600 psi. The total fuel weight for a fully-fueled vehicle is 375.5 lb.

Without regenerative braking, the fuel economy is 2.0675 lb/min. This yields a range of 181.6 miles. With regenerative braking, the fuel economy is 1.705 lb/min. This yields a range of 220.0 miles.

## Braking

Identical tests were conducted, both with and without regenerative braking, to determine its effectiveness. It appears that regenerative braking is more effective with capacitors. The benefits of regenerative braking with batteries are highly dependent on the state of charge of the batteries.

From an initial speed of 15.4 mph, the regenerative braking distance with capacitors was 103 feet, and the braking time was 10 seconds. The regenerative braking distance with batteries was 157 feet, and the braking time was 14 seconds. These results are plotted in Fig. 8.

Regenerative braking alone is sufficient to stop the vehicle in a Central Business District test using capacitors. A combination of regenerative and mechanical braking is required for batteries.

## Summary

An overall summary of the vehicle testing is shown in Table 2.

Fig. 7

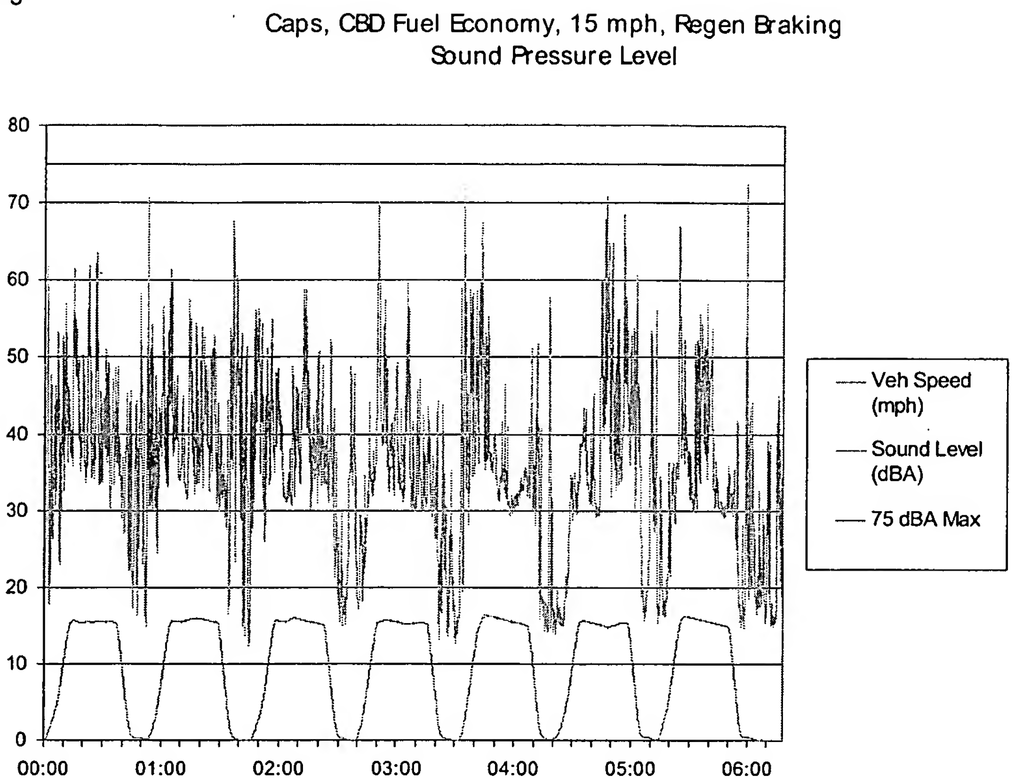
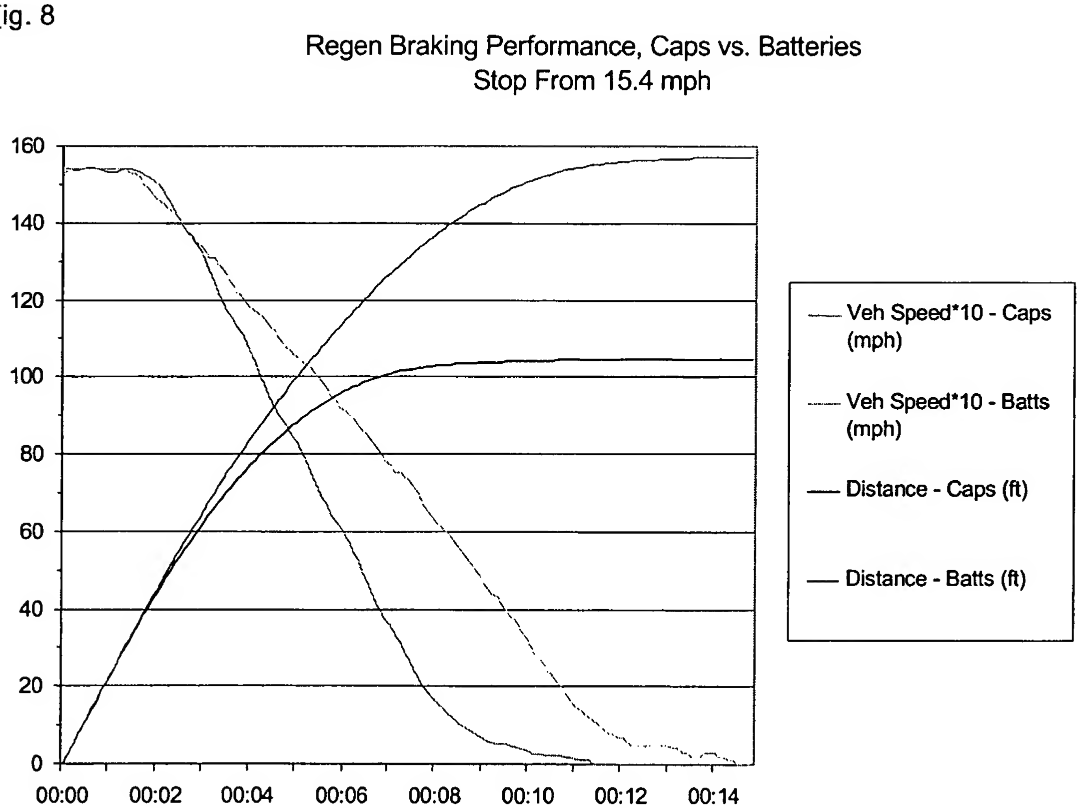

Caps, CBD Fuel Economy, 15 mph, Regen Braking
Sound Pressure Level
80
70
60
50
40
30
20
10
0
00:00
01:00
02:00
03:00
04:00
05:00
06:00
Veh Speed (mph)
Sound Level (dBA)
75 dBA Max

Fig. 8


Regen Braking Performance, Caps vs. Batteries
Stop From 15.4 mph
160
140
120
100
80
60
40
20
0
00:00
00:02
00:04
00:06
00:08
00:10
00:12
00:14
Veh Speed*10 - Caps (mph)
Veh Speed*10 - Batts (mph)
Distance - Caps (ft)
Distance - Batts (ft)

## Table 2 – Summary of Test Results for the Hybrid Electric Transit Bus

| Parameter | Configuration | Test Results | Remarks |
|---|---|---|---|
| Fuel Economy | Capacitors, No Regen Br<br>-----<br>Capacitors, With Regen Br | 3.01 mpg diesel<br>-----<br>3.65 mpg diesel | 4 miles CBD,<br>(28 cycles)<br>@ 15 mph |
| Top Speed | Batteries | 40 mph | Limited by maximum motor speed in first gear |
| Acceleration Times | | | |
| 10 mph | Capacitors<br>-----<br>Batteries | 8 sec<br>-----<br>6 sec | |
| 15 mph | Capacitors<br>-----<br>Batteries | 11 sec<br>-----<br>9 sec | |
| 20 mph | Batteries | 12 sec | |
| 30 mph | Batteries | 22 sec | |
| 35 mph | Batteries | 35 sec | |
| Average Acceleration | Capacitors<br>-----<br>Batteries | 0.062 g<br>-----<br>0.076 g | 0-15 mph |
| Maximum Acceleration Jerk | Capacitors<br>-----<br>Batteries | 0.04 g/s<br>-----<br>0.06 g/s | 0-15 mph |
| Maximum Deceleration Jerk | Capacitors<br>-----<br>Batteries | -0.06 g/s<br>-----<br>-0.03 g/s | With Regenerative Braking |
| Gradeability | Capacitors<br>-----<br>Batteries | 2.77 %<br>-----<br>3.39 % | At 15 mph |
| Sound Level | Capacitors | 73 dBA max<br>-----<br>40 dBA avg | 1 mile CBD,<br>(7 cycles)<br>@ 15 mph |
| Range | Capacitors, No Regen Br<br>-----<br>Capacitors, With Regen Br | 181.6 miles<br>-----<br>220.2 miles | 2683scf CNG @ 3600 psi |
| Regenerative Braking Distance | Capacitors<br>-----<br>Batteries | 103 ft<br>-----<br>157 ft | From 15.4 mph<br>No mechanical braking used |
| Regenerative Braking Time | Capacitors<br>-----<br>Batteries | 10 sec<br>-----<br>14 sec | From 15.4 mph<br>No mechanical braking used |

## CONCLUDING REMARKS

The HETB as tested and described in this report is a proof-of-concept prototype with several known limitations. A conventional bus, fully loaded with passengers, has a weight of around 33,000 lb. The HETB had a measured weight of 37,600 lb. This extra weight, mostly attributed to having redundant energy storage systems, had a significant impact on vehicle performance. The size and weight of commercially available capacitors limited the amount of capacitance that could be installed. The APU was designed for use with lead acid batteries, not optimized for capacitors. Also its 39 kW maximum output power was known to be insufficient.

It was difficult to accelerate the vehicle to above 20 mph on capacitors. However, the data suggest that raising the total capacitance and the APU output power is all that is required to match the performance of the battery energy storage system. Under battery power, the drive train performed very well in terms of acceleration and top speed in first gear.

The test results did clearly demonstrate that capacitors are superior to batteries in delivering load currents to the traction motor when accelerating. They are also better at accepting regenerative braking currents, allowing for less usage of the mechanical brakes. The project team believes that the advantages of capacitors warrant further development efforts.

Future plans for the HETB call for the replacement of the present APU with a turbine driven APU, increasing the capacitor energy storage bank while reducing its present weight and volume, redesigning the gearbox with integrated hydraulic circuits and developing a fully integrated power management and control system.

## REFERENCES


1. "Baseline Advanced Design Transit Coach Specifications", Department of Transportation, 1978.
2. Viterna, L.A., "Hybrid Electric Transit Bus", NASA Technical Memorandum 113176, October, 1997.

## APPENDIX A

## VEHICLE SUMMARY DATA SHEET

| | |
|---|---|
| 1.0 Vehicle Manufacturer | Flxible, Inc., Delaware, OH |
| 2.0 Vehicle | Flxible Metro Model 40102 Conversion |
| 3.0 Vehicle Configuration | Series Hybrid with Regenerative Braking |
| 4.0 Traction Motor | |
| 4.1 Traction Motor Configuration | 3-phase Induction |
| 4.2 Traction Motor Horsepower | 200 HP |
| 4.3 Traction Motor Speed Range | 0-10000 rpm |
| 4.4 Traction Motor Cooling | Liquid cooled |
| 5.0 Drivetrain | |
| 5.1 Transmission Type | 2 speed manual |
| 5.2 Gear Ratios | 7.6 to 1 First Gear,<br>4.8 to 1 Second Gear |
| 5.3 Axle Ratio | 4.7 to 1 |
| 5.4 Final Drive Ratio | 35.5 to 1 First Gear,<br>22.4 to 1 Second Gear |
| 6.0 Auxiliary Power Unit (APU) | |
| 6.1 Engine Configuration | 5-cylinder In-line |
| 6.2 Engine Displacement | 2.3 liter |
| 6.3 Engine Horsepower | 90 HP |
| 6.4 Engine Speed Range | 2100 to 4500 rpm |
| 6.5 Engine Fuel | Compressed Natural Gas (CNG) |
| 6.6 Generator Type | 12 Pole, 3-phase, Wound Field |
| 6.7 Generator Power | 50 kW |
| 6.8 Generator Voltage | 250 to 360 VDC |
| 7.0 Vehicle Dimensions | |
| 7.1 Wheel Base | 299 in (7.59 m) |
| 7.2 Length | 40 ft, 8.4 in (12.41 m) |
| 7.3 Track | 85.66 in (2.18 m) front,<br>76.50 in (1.94) rear |
| 7.4 Width | 102 in (2.59 m) |
| 7.5 Height | 121.25 in (3.08 m) |
| 7.6 Base Curb Weight | 26054 lb (11814 kg) |
| 7.7 Total Weight (as tested) | 37600 lb (17055 kg) |
| 7.8 Fuel Capacity | 8050 scf total @ 3600 psig max |

| | |
|---|---|
| 8.0 Accessories | |
| 8.1 Auxiliary Motor Configuration | 3-phase Induction |
| 8.2 Auxiliary Motor Horsepower | 25 HP |
| 8.3 APU Fan Motor Configuration | 3-phase Induction |
| 8.4 APH Fan Motor Horsepower | 3 HP |
| 8.5 Accessory and APU Motor Cooling | Totally Enclosed Air Cooling |
| 9.0 Energy Storage | |
| 9.1 Capacitors | |
| 9.1.1 Configuration | Bank of 30 ultra-capacitors (15 legs of two capacitors in series) |
| 9.1.2 Capacitance | 2.5 F each, 18.75 F total |
| 9.1.3 Energy Rating | 50 kJ each, 1.6 MJ total |
| 9.1.4 Voltage Rating | 200 V each |
| 9.1.5 Dimensions | 9 in (229 mm) diameter x 12 in (305 mm) length |
| 9.1.6 Weight | 70.5 lb (32 kg) each, 2115 lb (959 kg) total |
| 9.2 Batteries | |
| 9.2.1 Configuration | Two banks of 28 batteries each |
| 9.2.2 Energy Rating | 180 kJ each, 5.04 MJ per bank |
| 9.2.3 Voltage Rating | 12 V each, 336 V per bank |
| 9.2.4 Dimensions | 10.0 in (254 mm) x 6.8 in (173 mm) x 7.9 in (200 mm) |
| 9.2.5 Weight | 45 lb (20.4 kg) each, 2520 lb (1143 kg) total (both banks) |

APPENDIX B

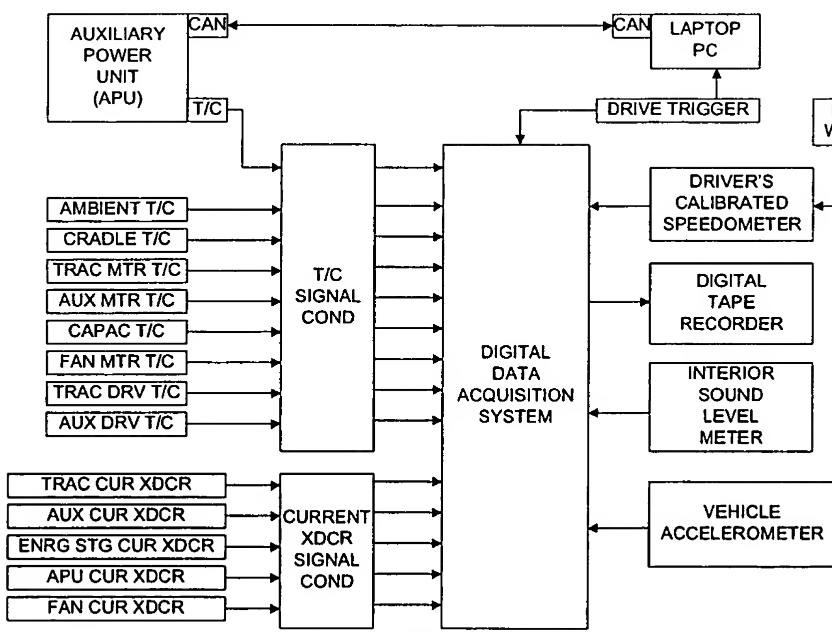
DESCRIPTION OF THE INSTRUMENTATION SYSTEM

A block diagram of the HETB instrumentation system is shown in Fig. B-1.

The APU has an integral instrumentation system that monitors APU output voltage, output current, engine speed, coolant temperature and oil pressure. These data are sampled at 1 Hz and transmitted to the laptop PC via a controller area network (CAN) interface. The PC logs the APU data. A type J thermocouple was mounted on the APU to monitor its temperature.

All other measurements were obtained with a MegaDAC data acquisition system, sampling at 100 Hz. Type J thermocouples were used for all temperature measurements. Hall effect transducers were used for all current measurements. A fifth wheel installed on the back of the HETB provided vehicle speed and distance measurements. These data were sent to a calibrated speedometer for the driver, as well as to the data acquisition system. An accelerometer mounted near the vehicle's center of mass provided the acceleration and jerk data. A sound pressure level sensor was positioned behind the driver's seat at ear level, 45 inches from the floor. The laptop PC was externally synchronized with the data acquisition system.

Fig. B-1




**HETB INSTRUMENTATION SYSTEM**

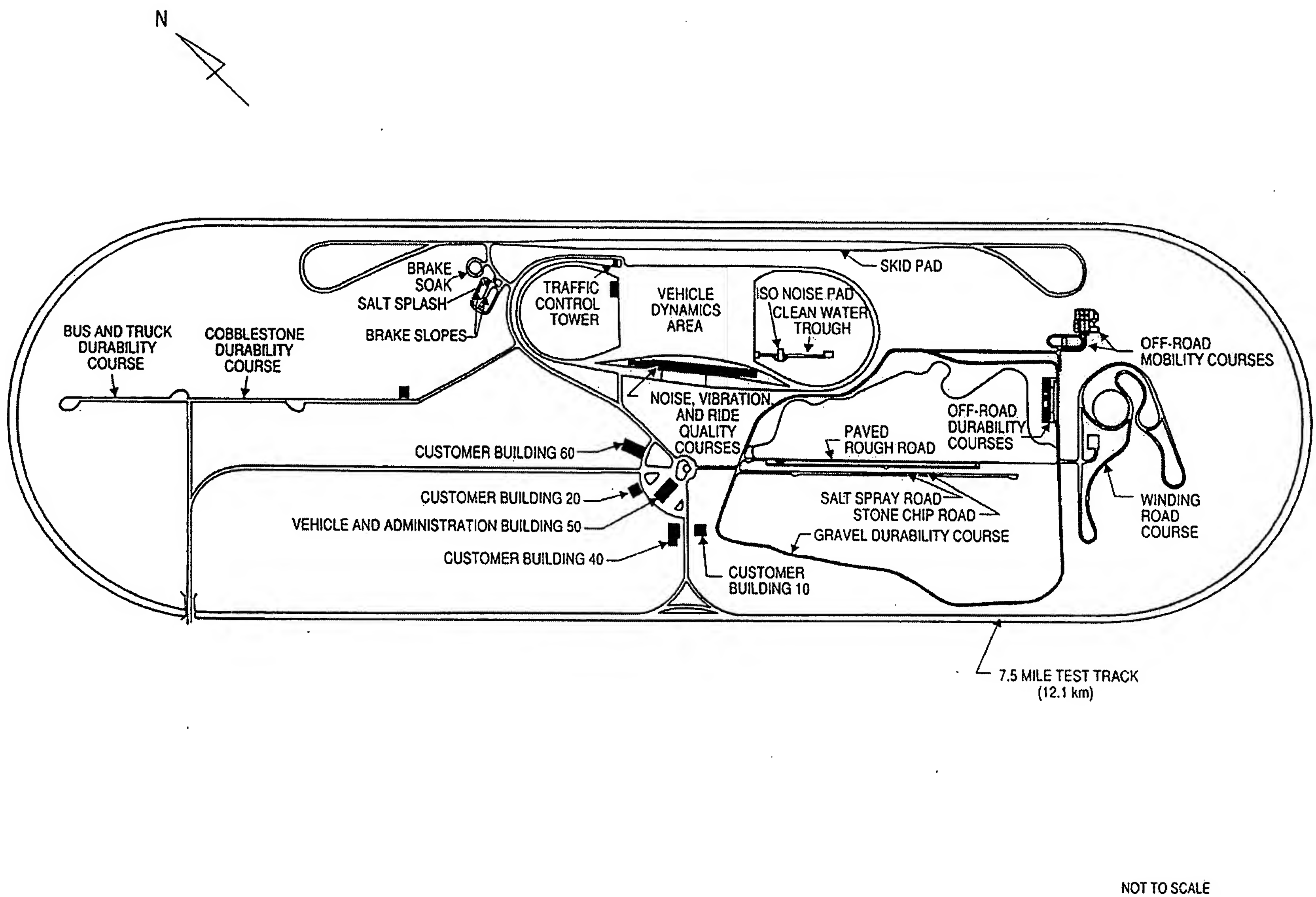
# APPENDIX C

## DESCRIPTION OF VEHICLE TEST TRACK

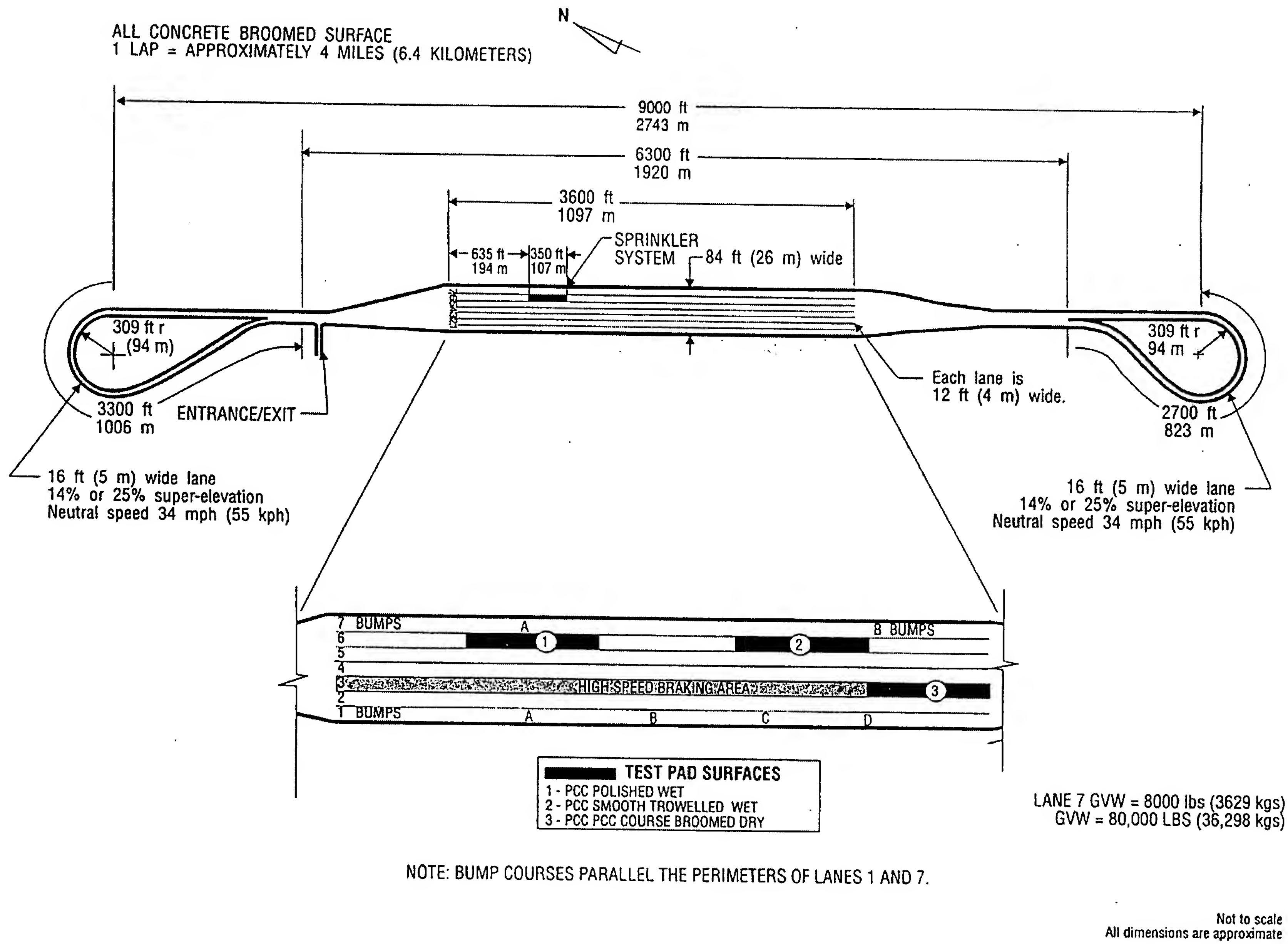
The track used to conduct the tests described in this report is the Transportation Research Center, located in East Liberty, Ohio. A facility map is shown in Fig. C-1.

Preliminary tests were conducted on the skid pad. This concrete broomed track is a four-mile loop. The skid pad is shown in Fig. C-2.

Tests documented in this report were conducted on Lane 1 of the 7.5-mile test track. This lane is concrete with ten degree banking on the turns. This track is shown in Fig. C-3.

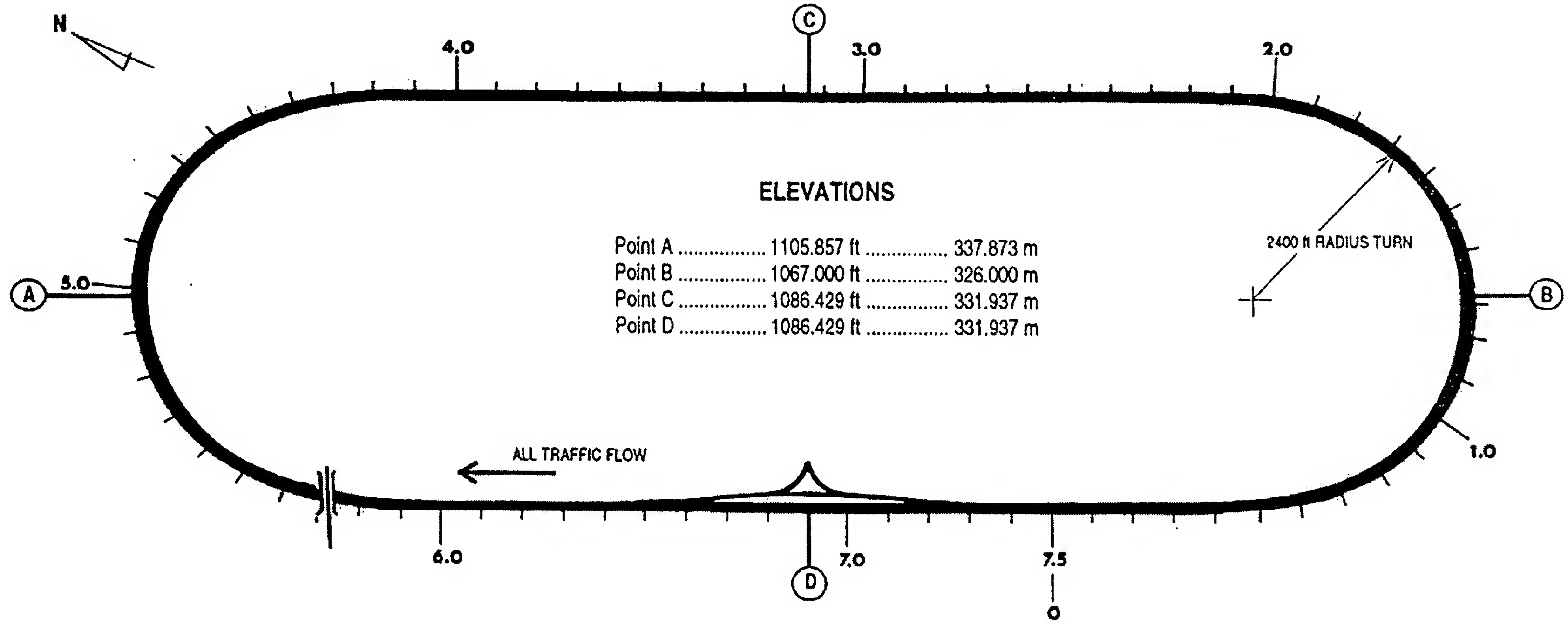



TEST FACILITY DETAIL



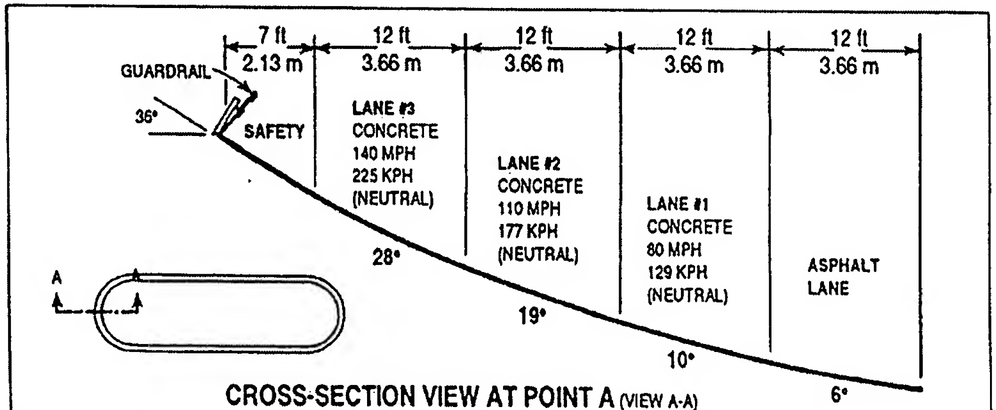
ALL CONCRETE BROOMED SURFACE
1 LAP = APPROXIMATELY 4 MILES (6.4 KILOMETERS)
N
9000 ft
2743 m
6300 ft
1920 m
3600 ft
1097 m
635 ft
194 m
350 ft
107 m
SPRINKLER SYSTEM
84 ft (26 m) wide
309 ft r
(94 m)
3300 ft
1006 m
ENTRANCE/EXIT
16 ft (5 m) wide lane
14% or 25% super-elevation
Neutral speed 34 mph (55 kph)
309 ft r
94 m
Each lane is
12 ft (4 m) wide.
2700 ft
823 m
16 ft (5 m) wide lane
14% or 25% super-elevation
Neutral speed 34 mph (55 kph)
7 BUMPS
A
B BUMPS
HIGH SPEED BRAKING AREA
1 BUMPS
A
B
C
D
TEST PAD SURFACES
1 - PCC POLISHED WET
2 - PCC SMOOTH TROWELLED WET
3 - PCC PCC COURSE BROOMED DRY
LANE 7 GVW = 8000 lbs (3629 kgs)
GVW = 80,000 LBS (36,298 kgs)
NOTE: BUMP COURSES PARALLEL THE PERIMETERS OF LANES 1 AND 7.
Not to scale
All dimensions are approximate


SKID PAD




PLAN VIEW OF 7 1/2-MILE TRACK

GWV = 80,000 LBS (36,298 kgs)




CROSS-SECTION VIEW AT POINT A (VIEW A-A)

**DISTANCES**

| | | |
|---|---|---|
| Lane 3 | 7.539 mi | 12.133 km |
| Lane 2 | 7.521 mi | 12.104 km |
| Lane 1 | 7.507 mi | 12.081 km |
| Point A to Point B | 3.333 mi | 5.364 km |
| Point C to Point D | .947 mi | 1.524 km |

NOT TO SCALE

## 7.5-MILE TEST TRACK

## APPENDIX D

## DESCRIPTION OF TEST CYCLES

Testing of the HETB was based on the Department of Transportation Transit Bus White Book Specification (reference 1). The test matrix shown in table D-1 was derived from the White Book. The transit bus operating duty cycle is shown in Table D-2. The Central Business District (CBD) cycle of two miles with seven stops per mile and a top speed of 20 mph is shown in Fig. D-1. The Arterial Route Cycle of two miles with two stops per mile and a top speed of 40 mph is shown in Fig. D-2. The tests were actually run with top speeds of 15 mph and 35 mph, respectively. The minimum acceleration curve from the White Book is shown in Fig. D-3.

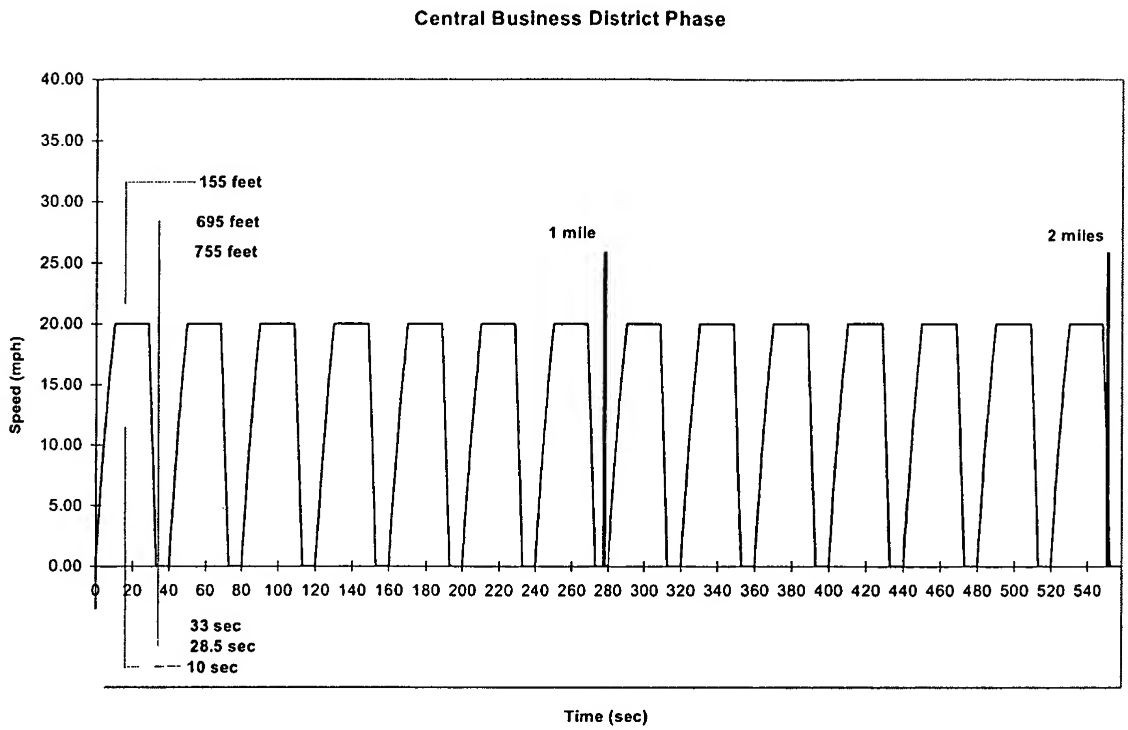
**Table D-1 Hybrid Electric Transit Bus Test Matrix**

| PARAMETER | CAP & APU REGEN | CAP & APU NO REGEN | BAT & APU REGEN | BAT & APU NO REGEN |
|---|---|---|---|---|
| Central Business District Cycle (20 mph max, 15 mph max as run). | Y | Y | Y | Y |
| Arterial Route Cycle (40 mph max , 35 mph max as run) | N | N | Y | Y |
| Top Speed (60 mph min with all accessories operating). | N | N | Y | Y |
| Gradeability (34 mph on a 2.5% grade, 7 mph on a 12% grade with all accessories operating). | Y | Y | Y | Y |
| Acceleration (0.06 g average between 0 and 15 mph). | Y | Y | Y | Y |
| Jerk (0.3 g max, accelerating and decelerating). | Y | Y | Y | Y |
| Sound Level (Central Business District Cycle) | Y | Y | Y | Y |
| Sound Level (Constant 20 mph). | Y | Y | Y | Y |
| Fuel Economy (Central Business District - see below). | Y | Y | N | N |

**Table D-2 Transit Coach Design Operating Duty Cycle**

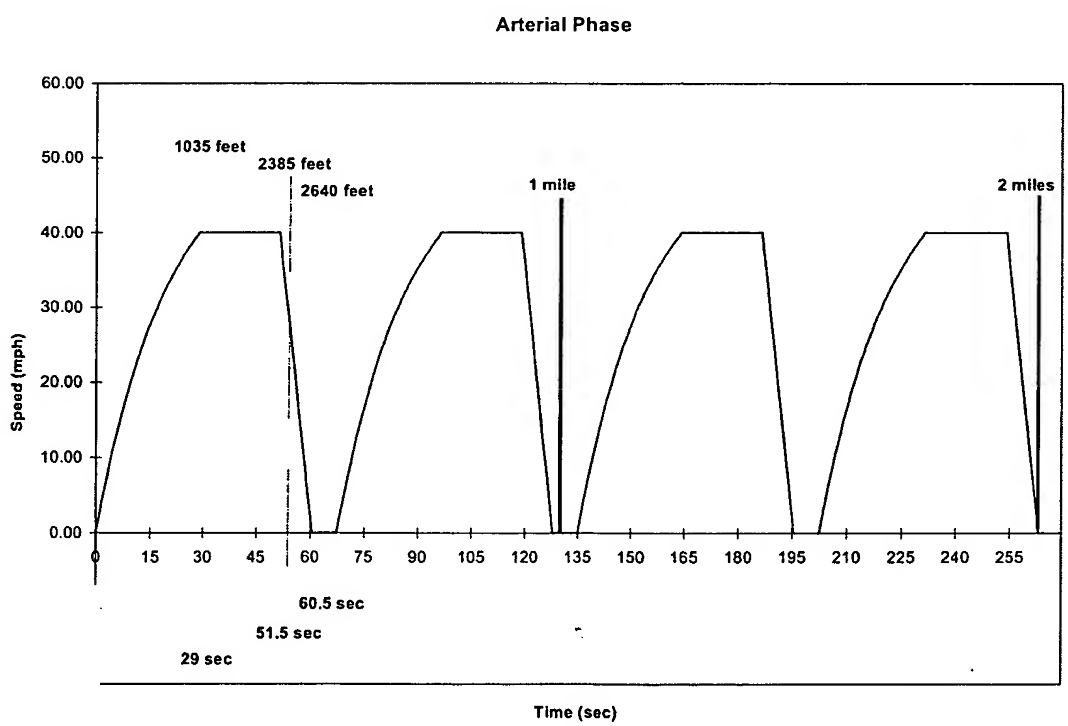
| PHASE | STOPS | TOP SPEED (MPH) | MILES | ACC DIST (FT) | ACC TIME (SEC) | CRUISE DIST (FT) | CRUISE TIME (SEC) | DEC RATE (FT/S/S) | DEC DIST (FT) | DEC TIME (SEC) | DWELL TIME (SEC) | CYC TIME (M-S) | TOT STOPS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CBD | 7 | 20 | 2 | 155 | 10 | 540 | 18.5 | 6.78 | 60 | 4.5 | 7 | 9-20 | 14 |
| IDLE | | | | | | | | | | | | 5-0 | |
| ART | 2 | 40 | 2 | 1035 | 29 | 1350 | 22.5 | 6.78 | 255 | 9 | 7 | 4-30 | 4 |
| CBD | 7 | 20 | 2 | 155 | 10 | 510 | 18.5 | 6.78 | 60 | 4.5 | 7 | 9-20 | 14 |
| ART | 2 | 40 | 2 | 1035 | 35 | 1350 | 22.5 | 6.78 | 255 | 9 | 7 | 4-30 | 4 |
| CBD | 7 | 20 | 2 | 155 | 10 | 510 | 18.5 | 6.78 | 60 | 4.5 | 7 | 9-20 | 14 |
| COMM | 1/PH | 55 | 4 | 5500 | 90 | 15140 | 188 | 6.78 | 480 | 12 | 20 | 5-10 | 1 |
| TOTAL | | | 14 | | | | | | | | | 47-10 | 51 |

Fig. D-1



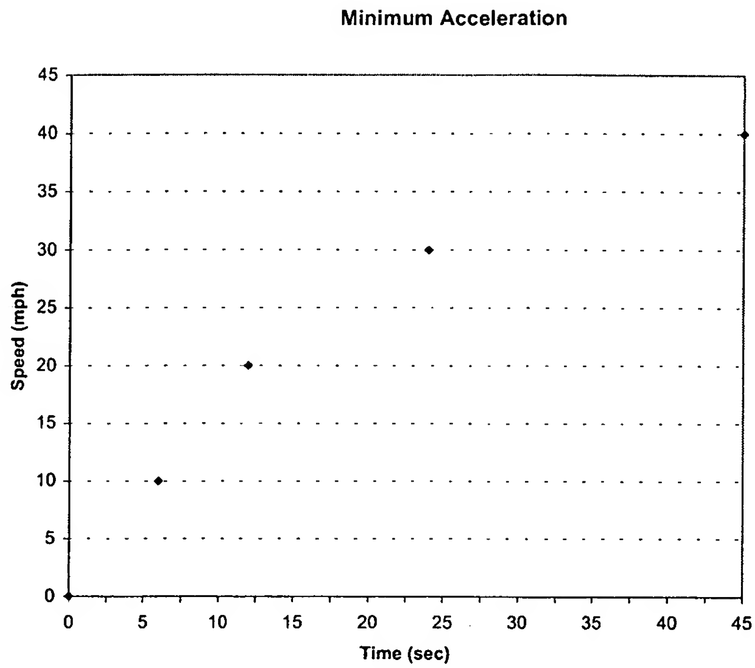
Central Business District Phase
Speed (mph)
Time (sec)
155 feet
695 feet
755 feet
1 mile
2 miles
33 sec
28.5 sec
10 sec


Fig. D-2



Arterial Phase
Speed (mph)
Time (sec)
1035 feet
2385 feet
2640 feet
1 mile
2 miles
60.5 sec
51.5 sec
29 sec

Fig. D-3



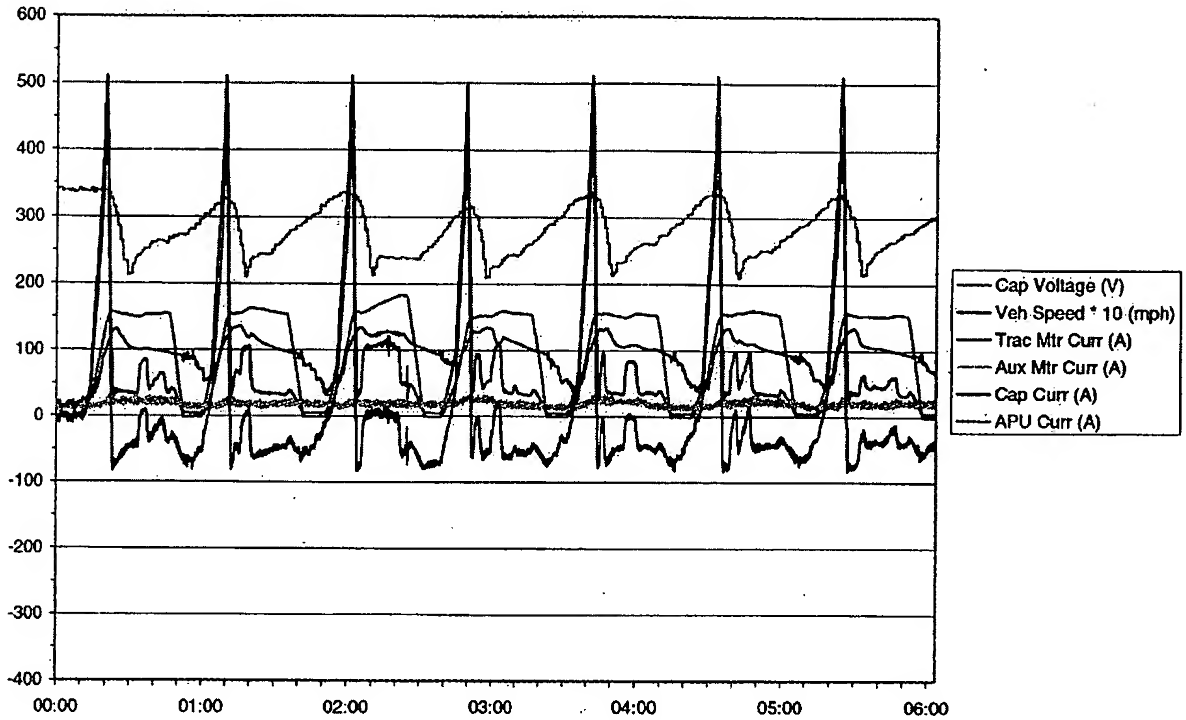
Minimum Acceleration
Speed (mph)
45
40
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
40
45
Time (sec)

# APPENDIX E

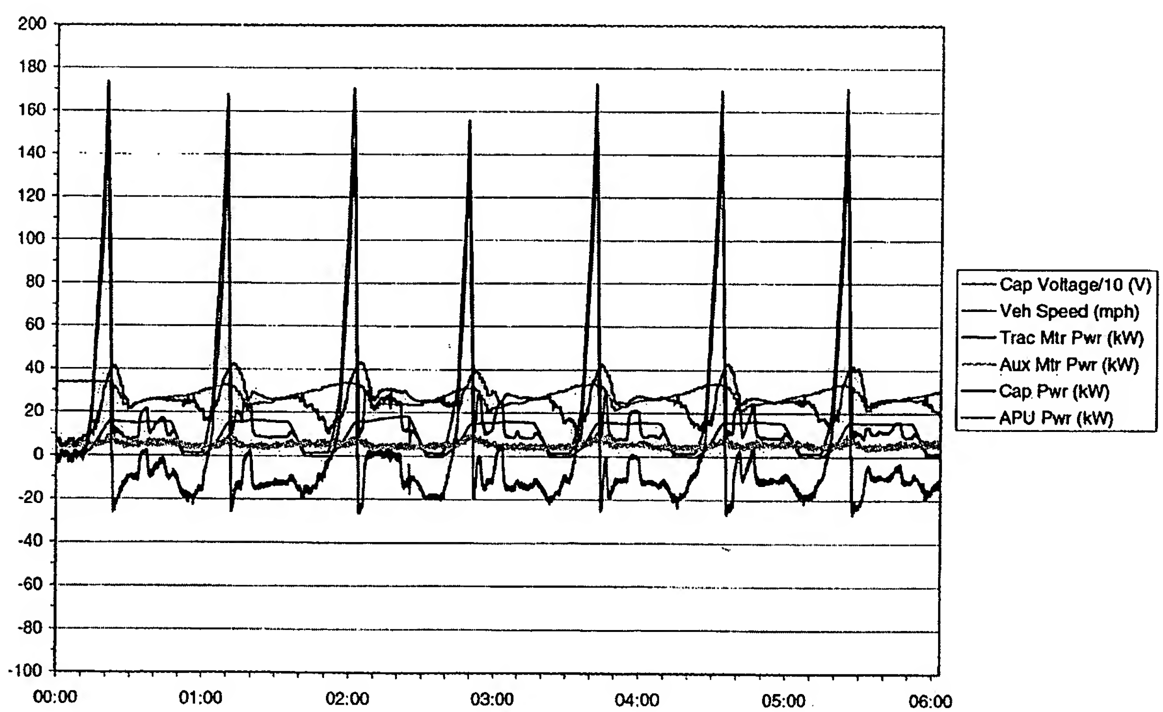
## VEHICLE PERFORMANCE TEST RESULTS

A complete set of plots of the test results are included here. Table 1 identifies the tests that were conducted.

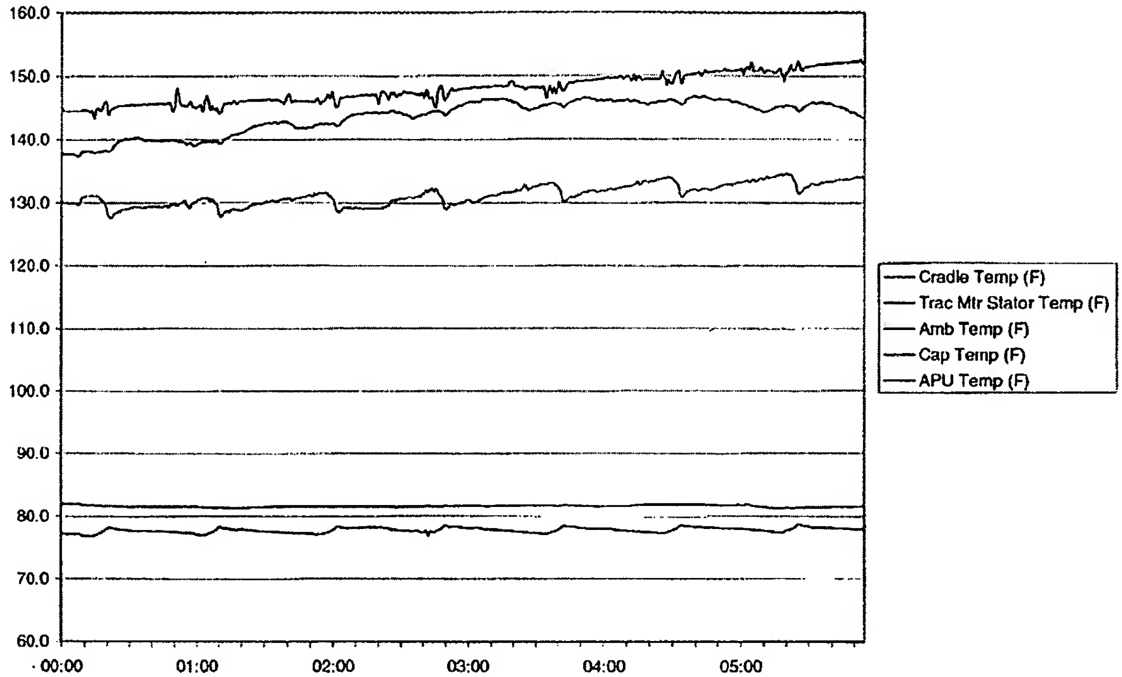
## Test 1: Caps, CBD Fuel Economy, 15 mph, No Regen Braking



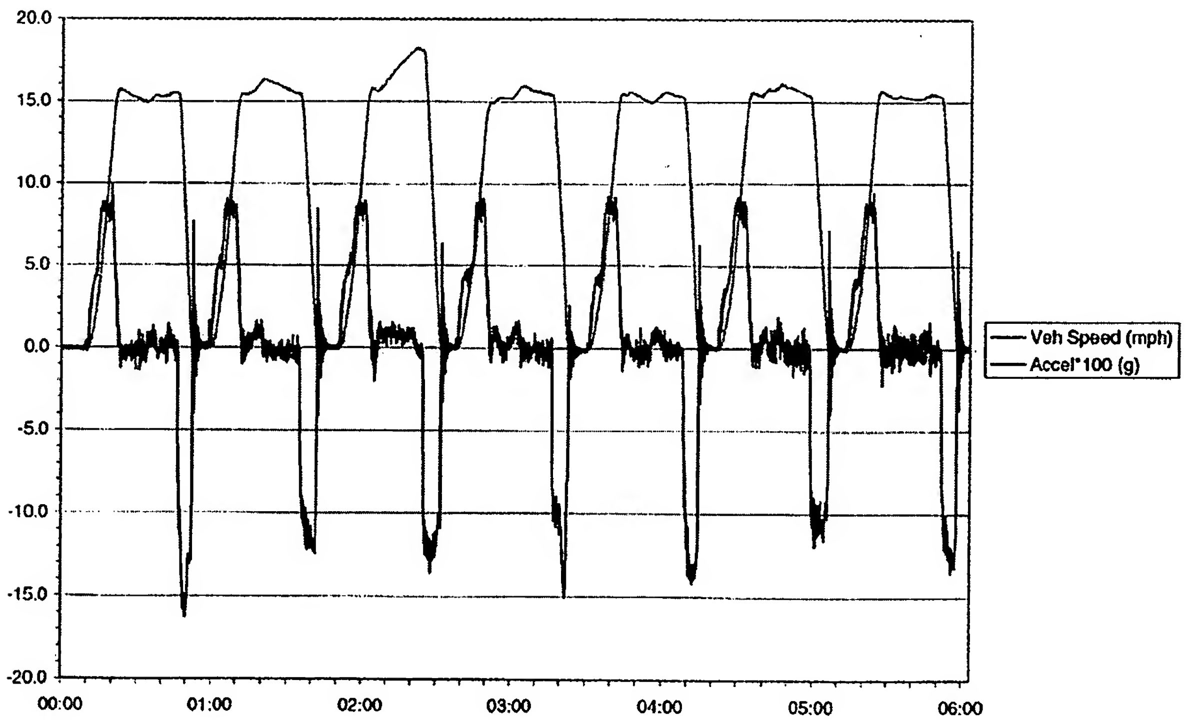

## Test 1: Caps, CBD Fuel Economy, 15 mph, No Regen Braking



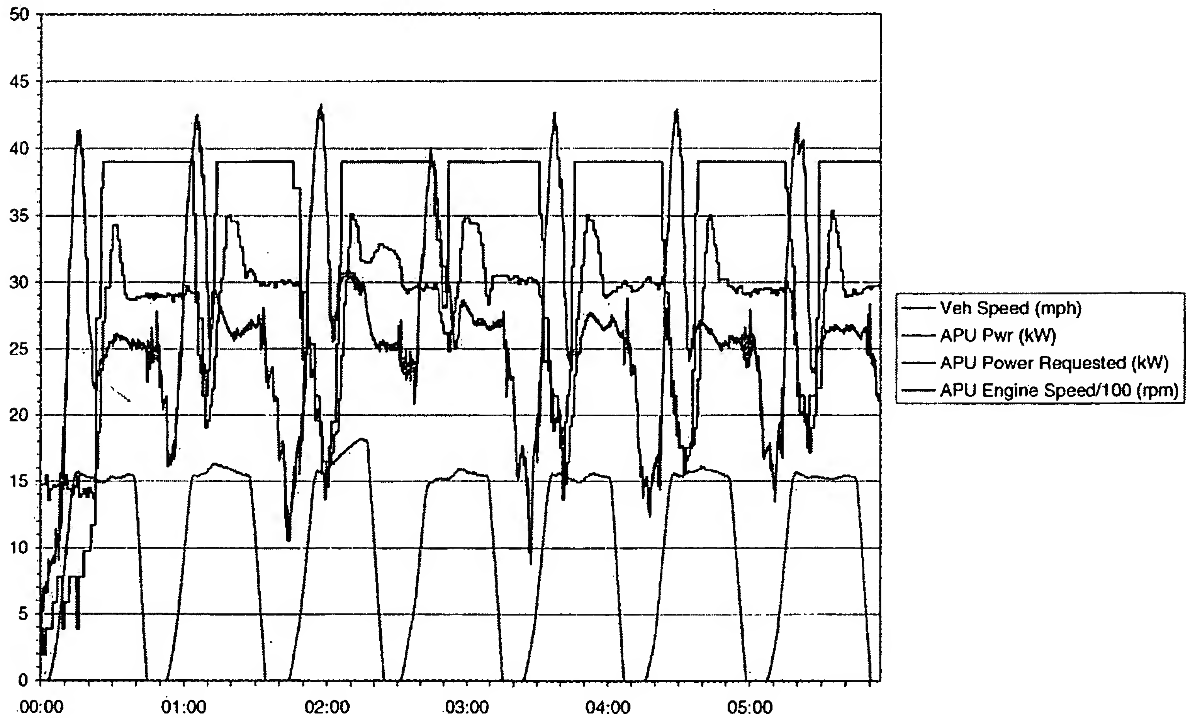
**Test 1: Caps, CBD Fuel Economy, 15 mph, No RegenBraking**




**Test 1: Caps, CBD Fuel Economy, 15 mph, No Regen Braking**



Test 1: Capacitors, CBD Fuel Economy, 15 mph, No Regen Braking

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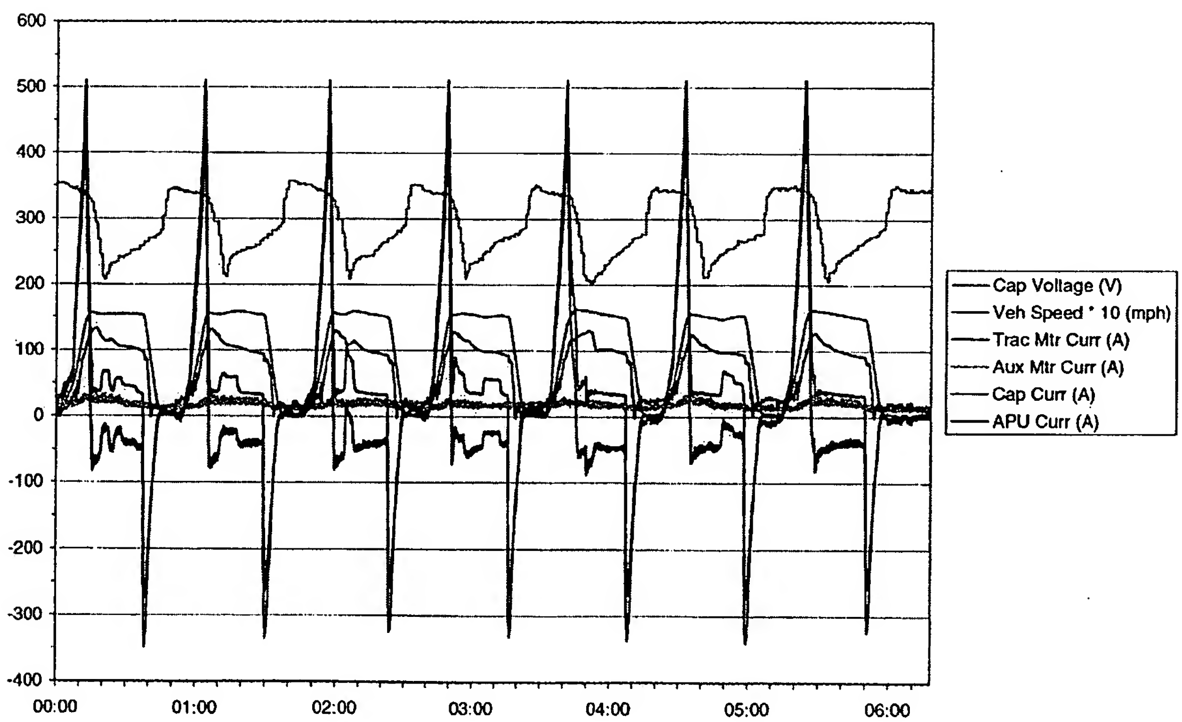

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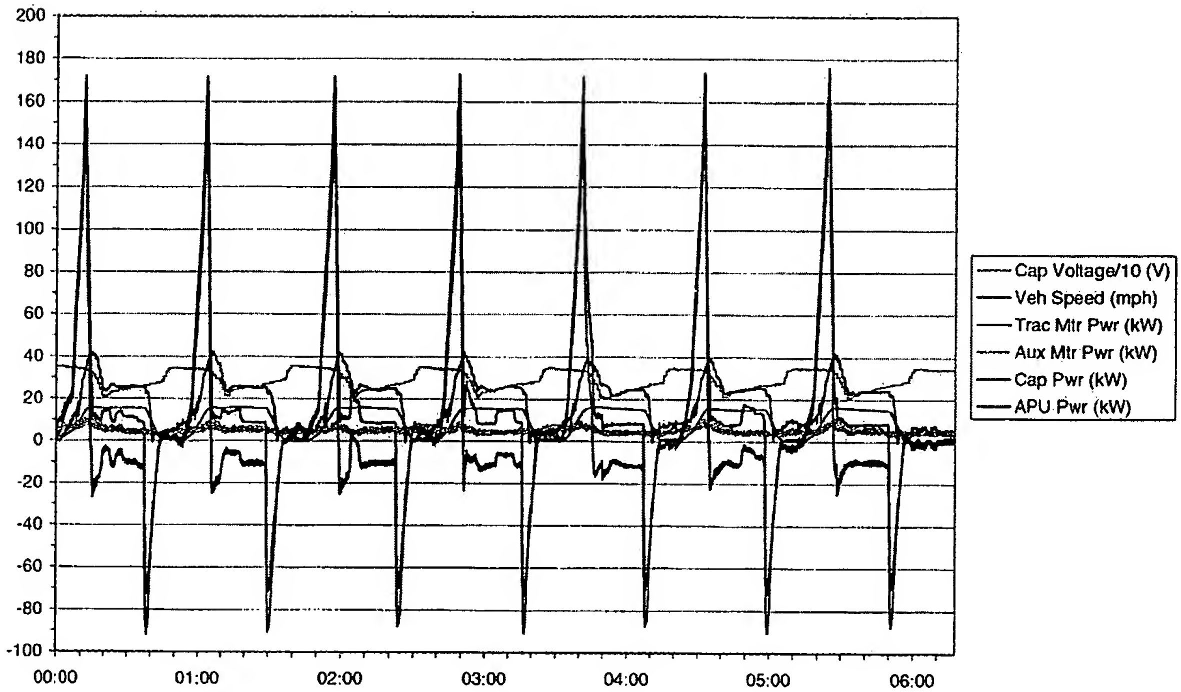


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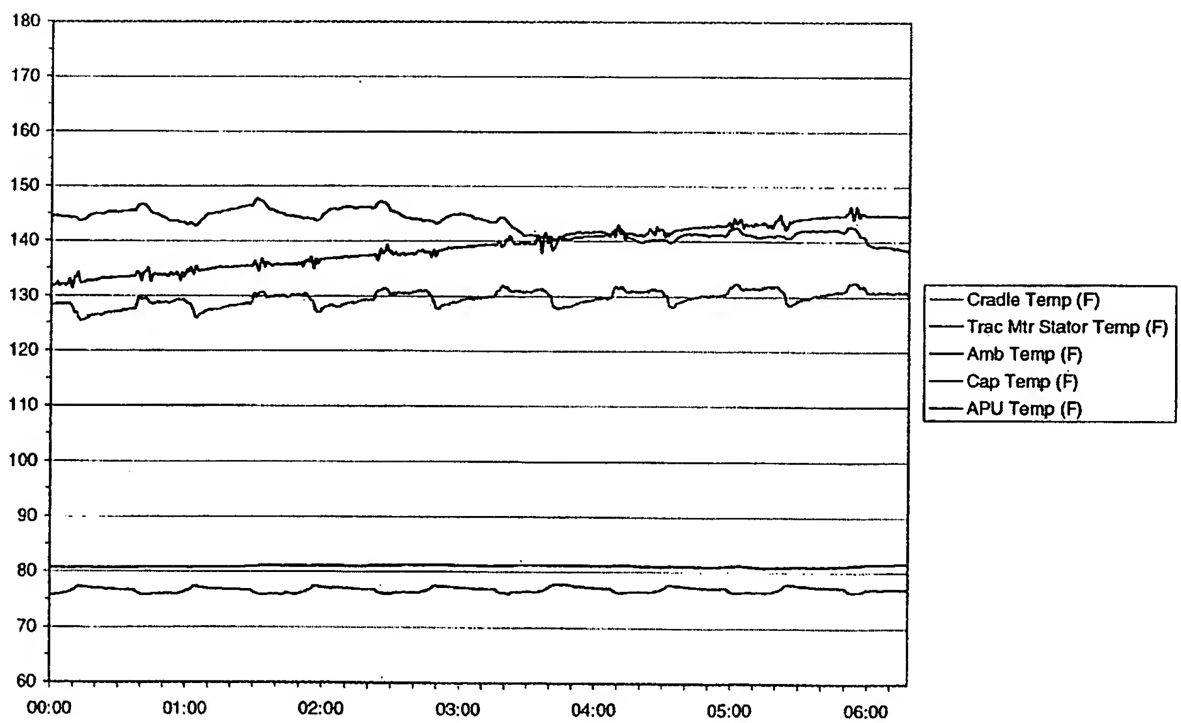

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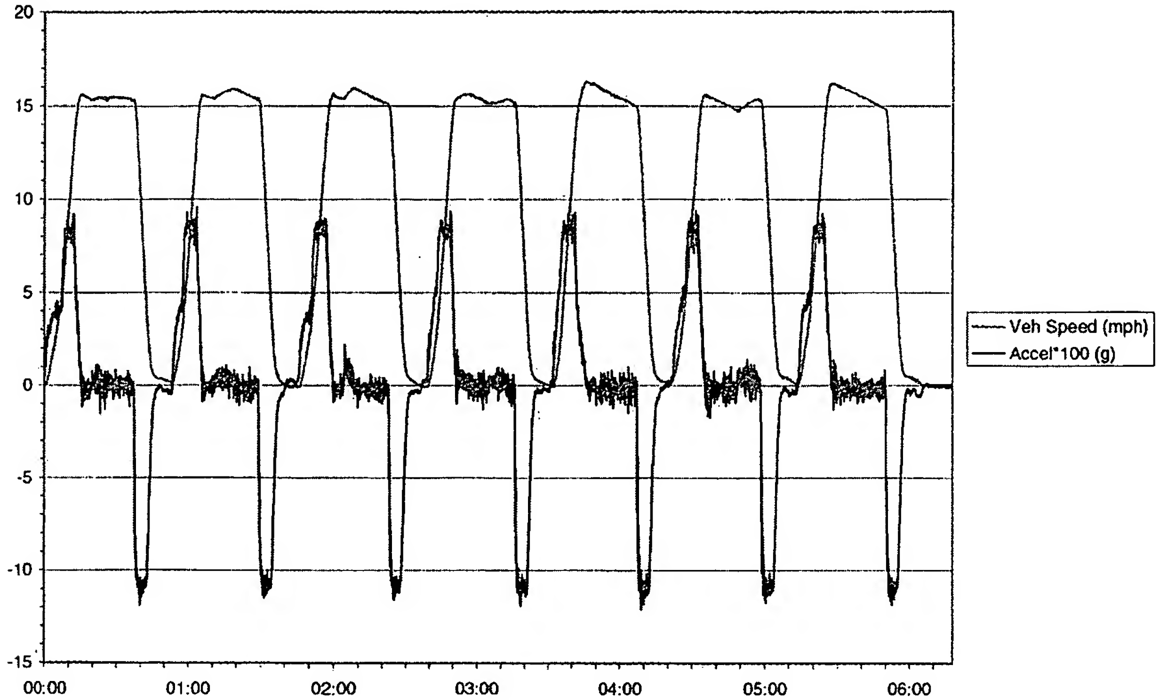


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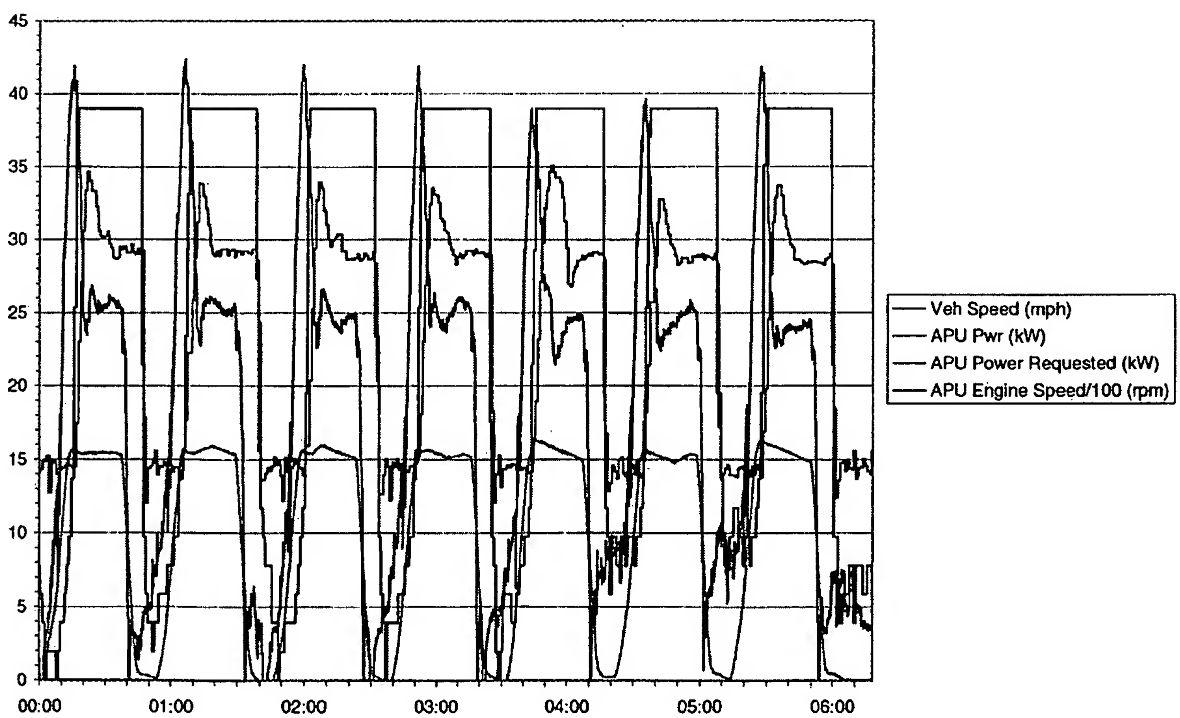

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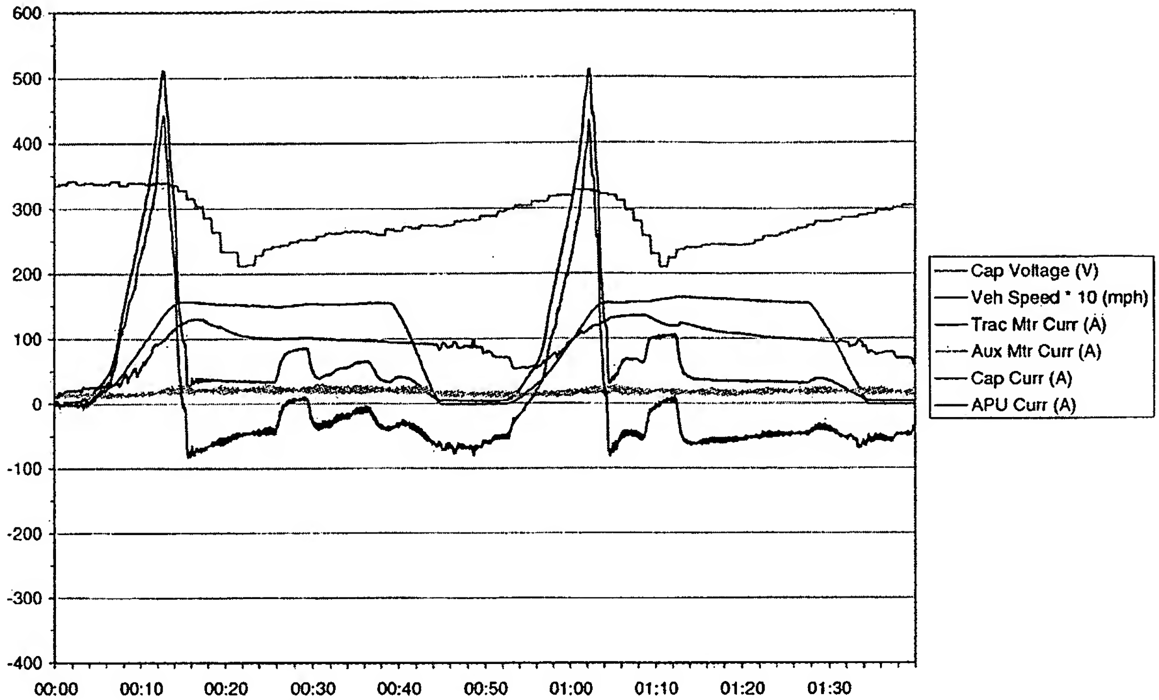


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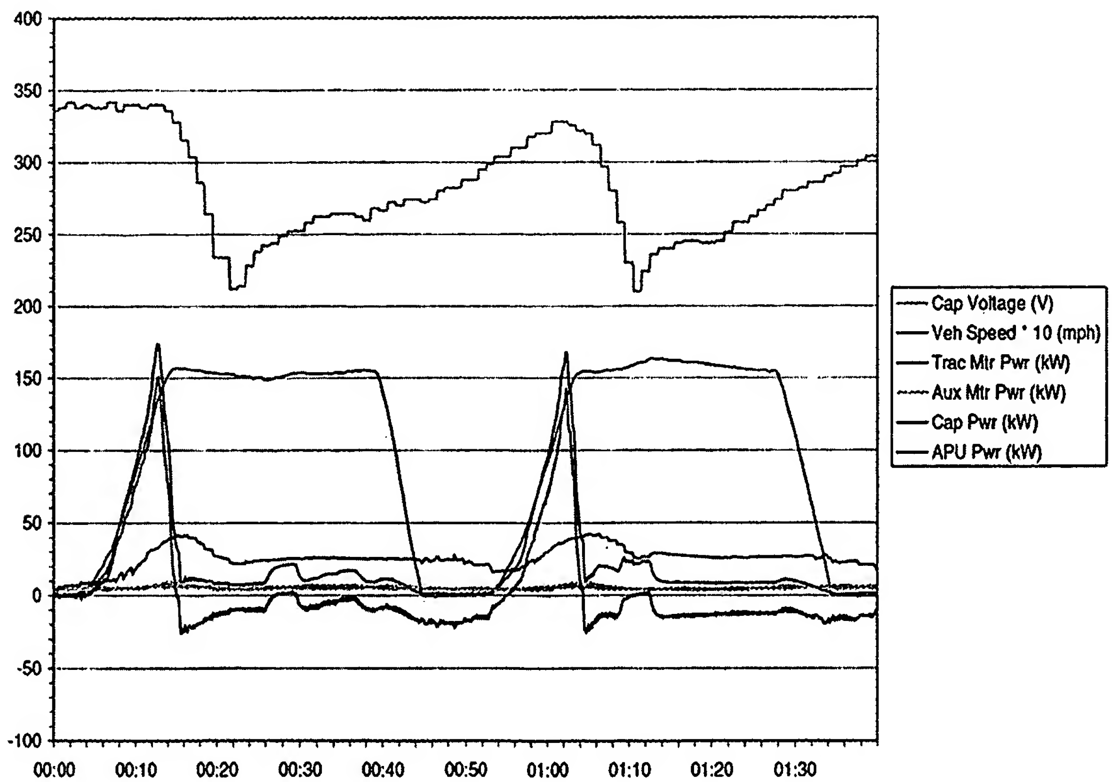

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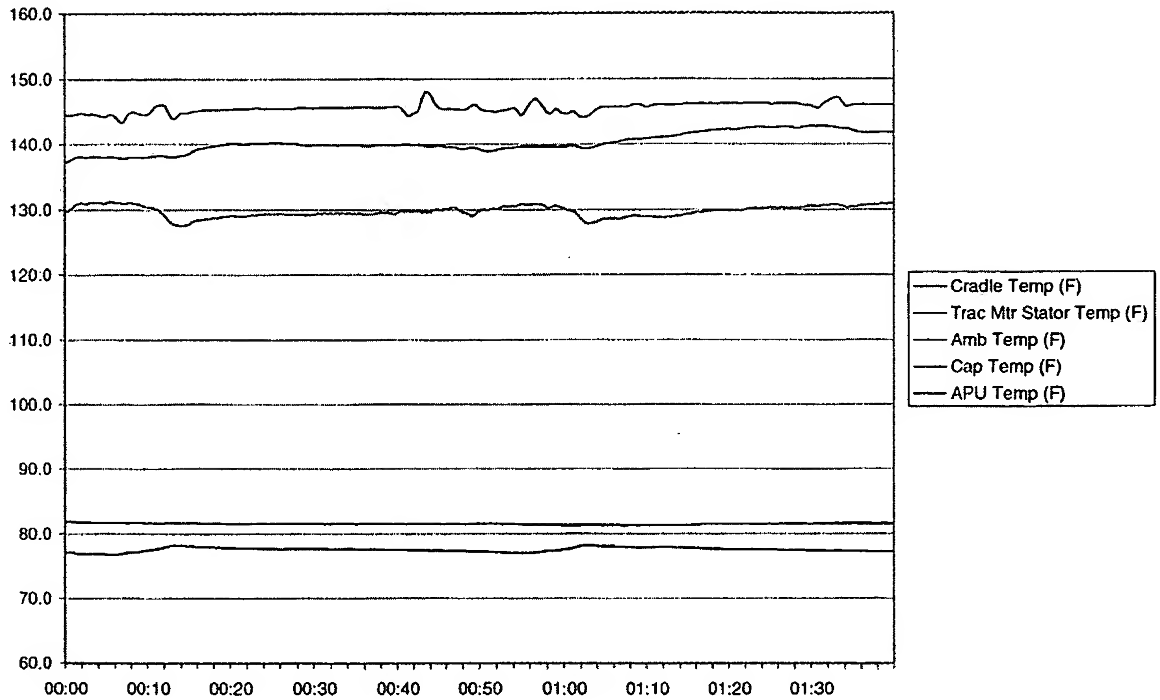


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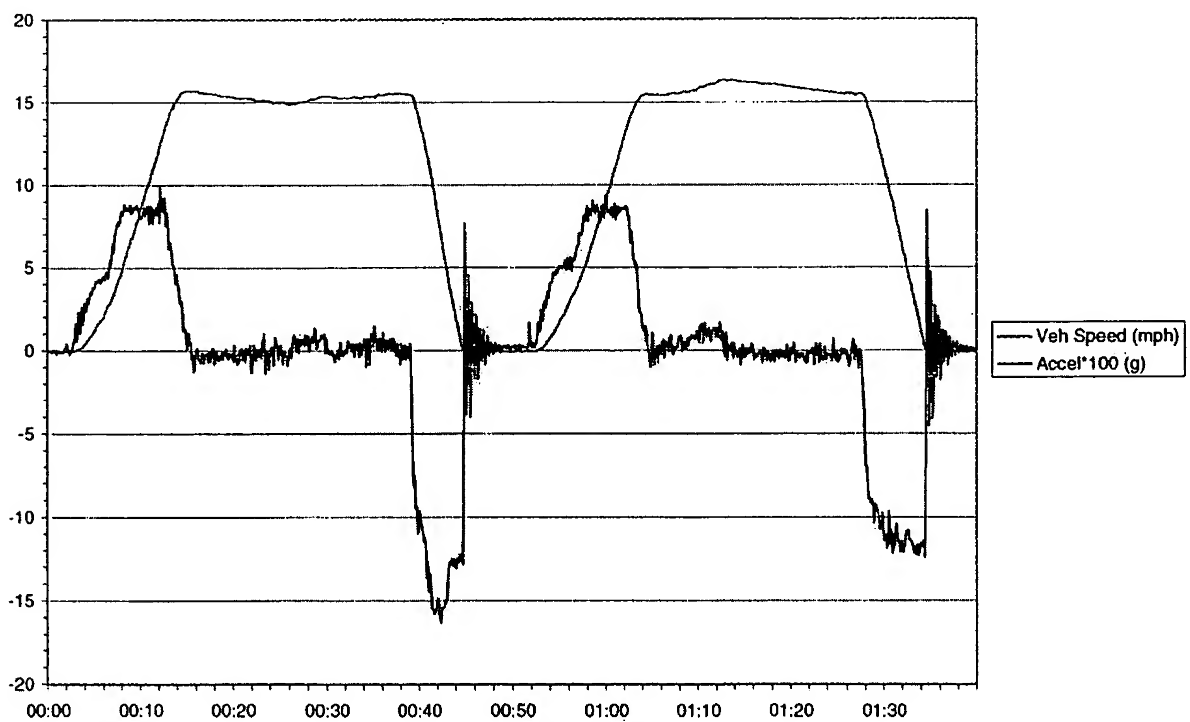
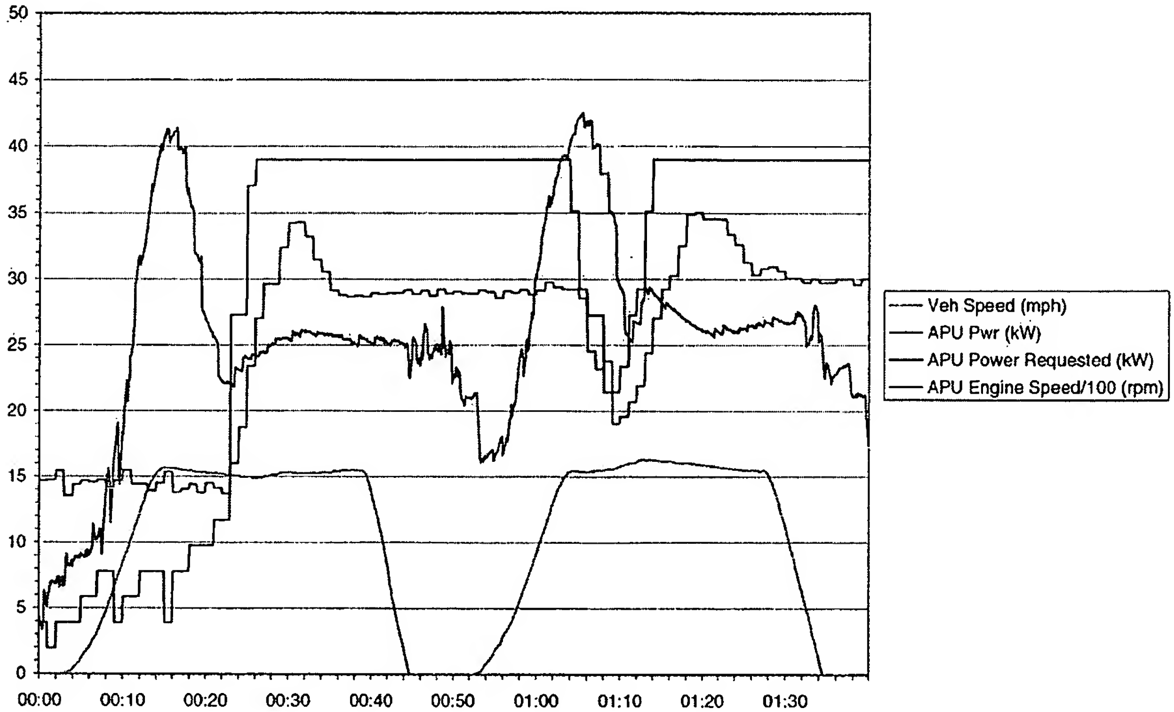


**Test 3: Capacitors, 0-15 mph, No Regen Braking**

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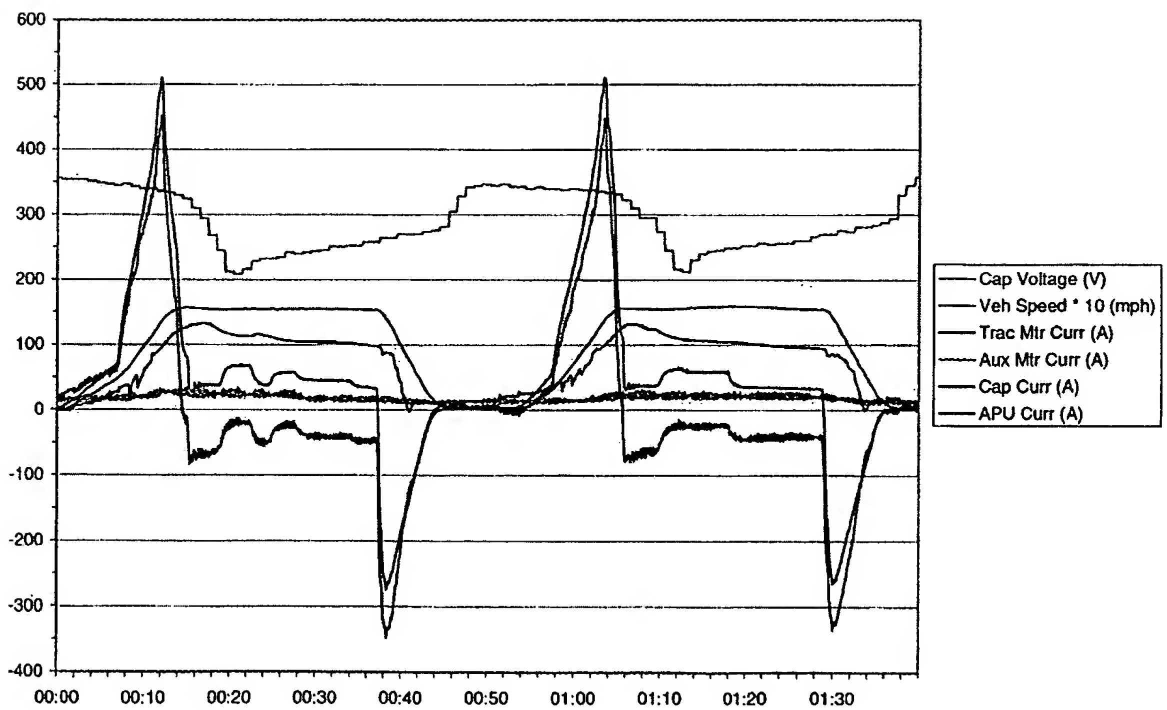

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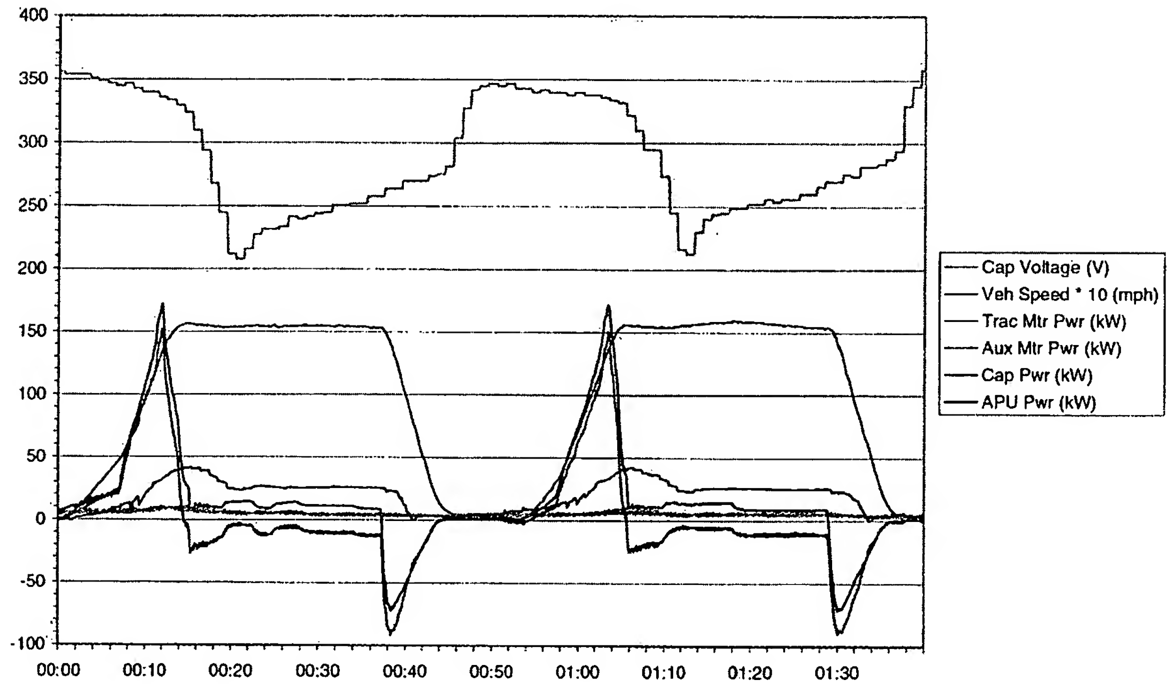


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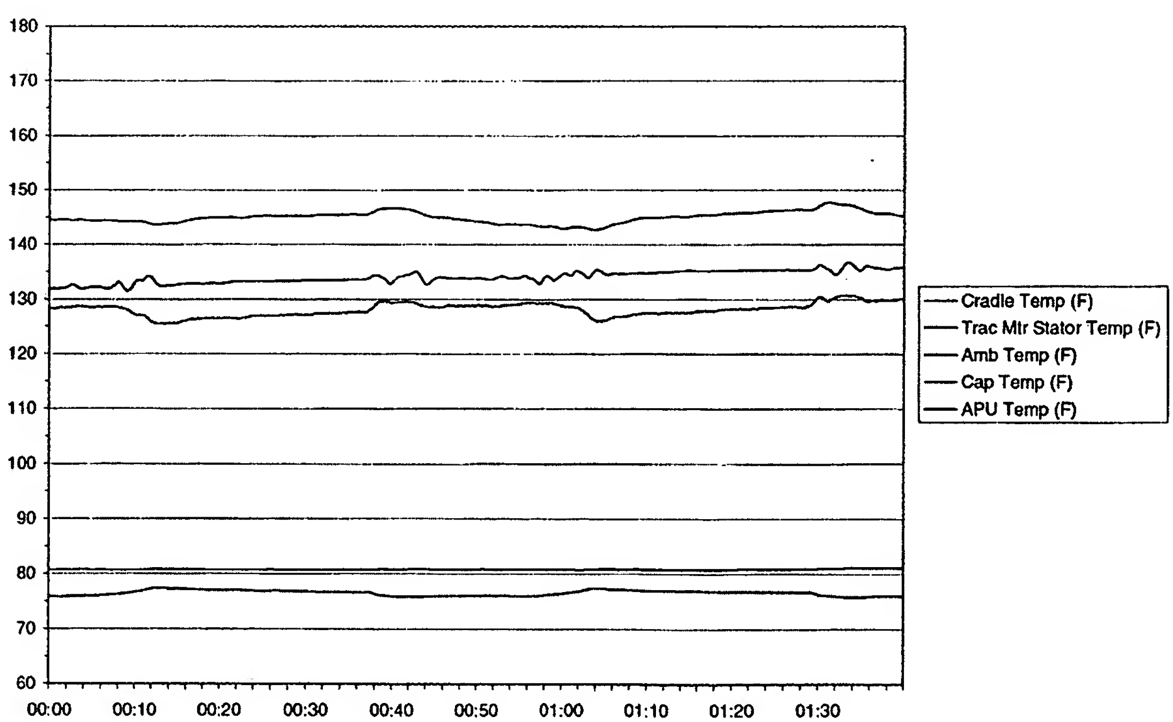

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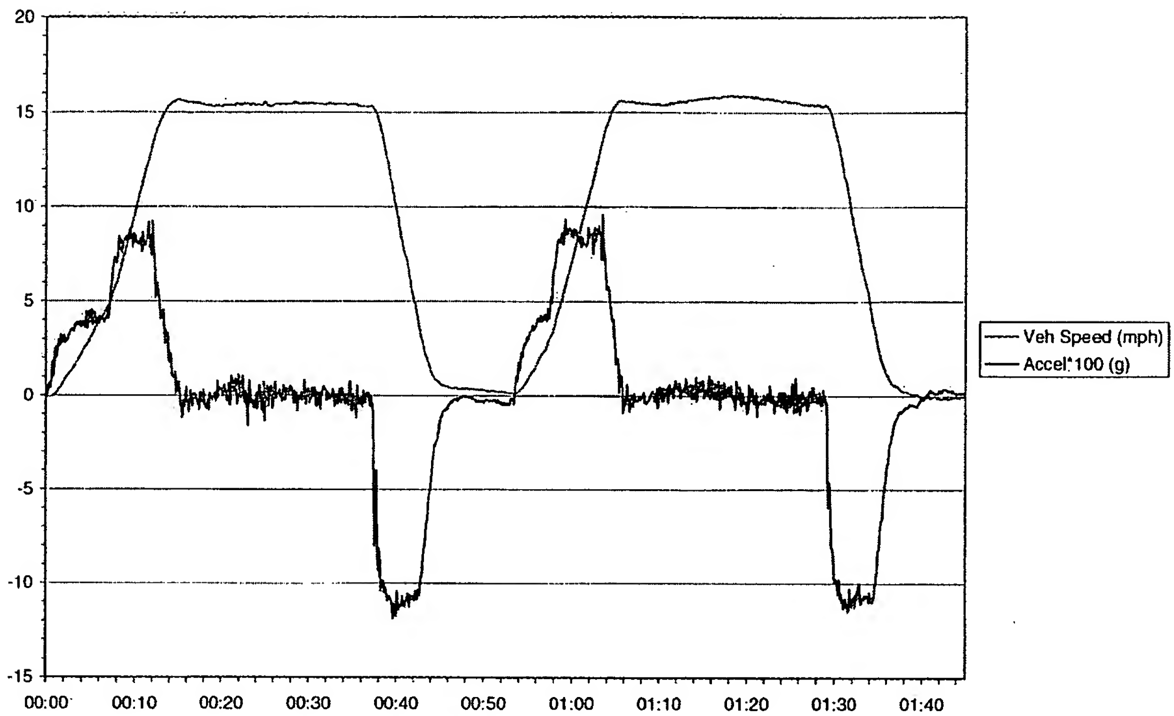


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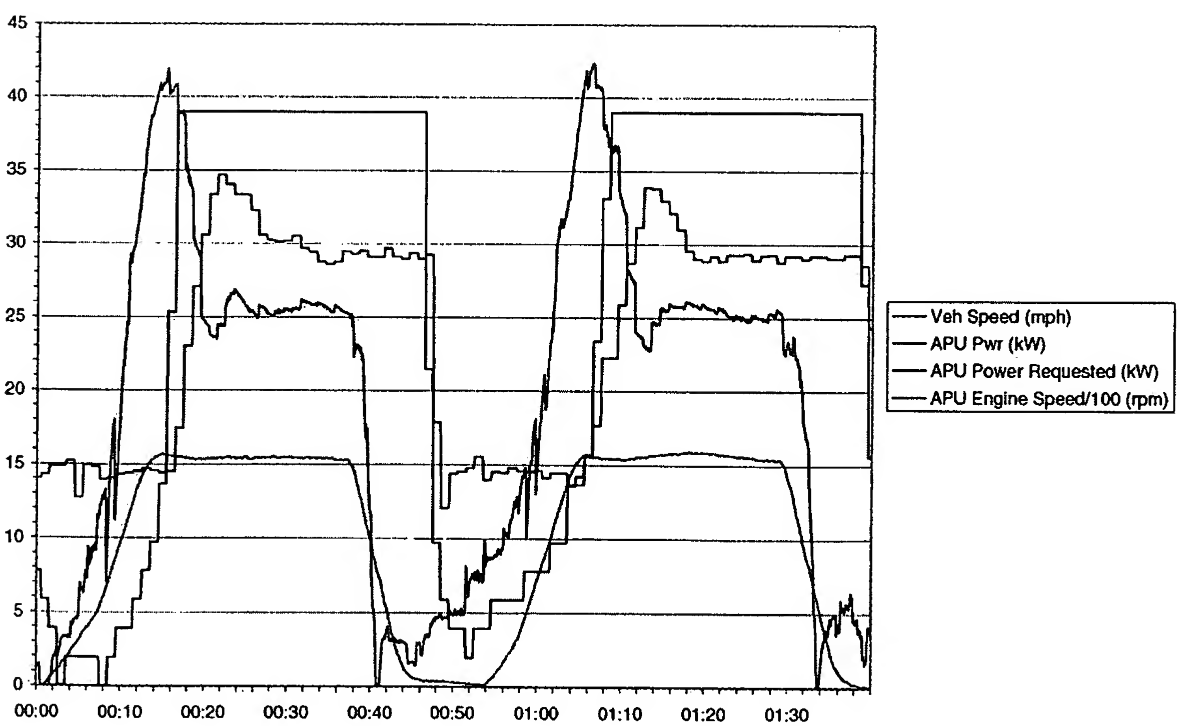

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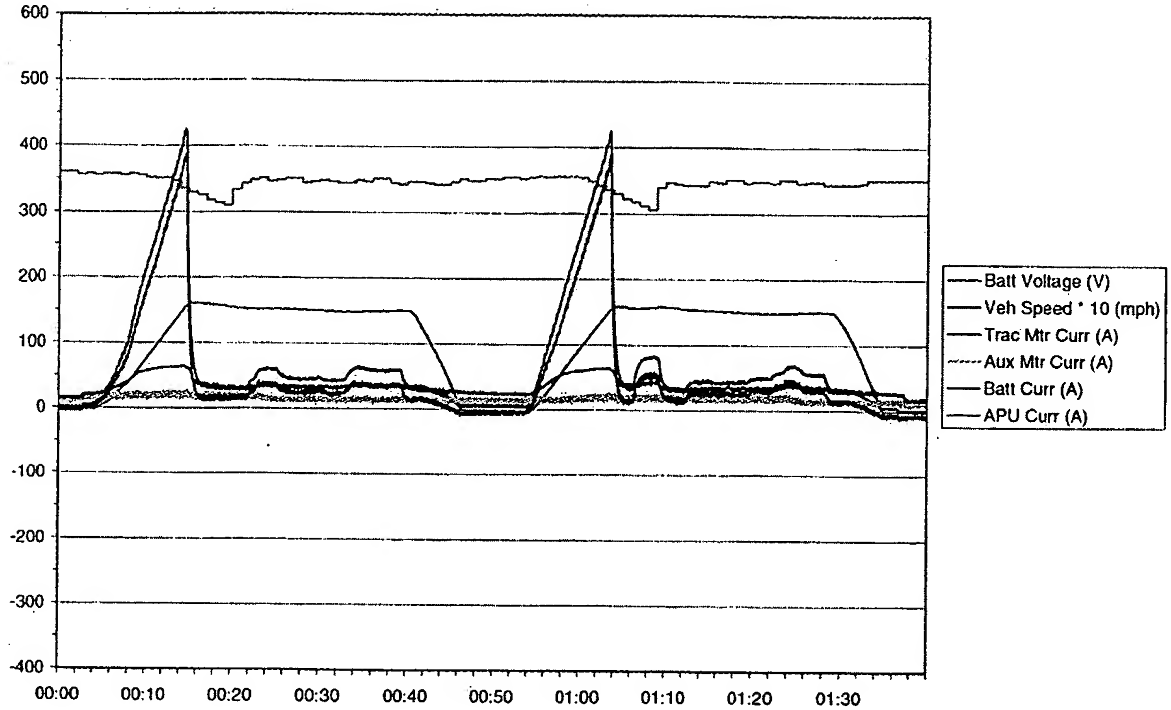


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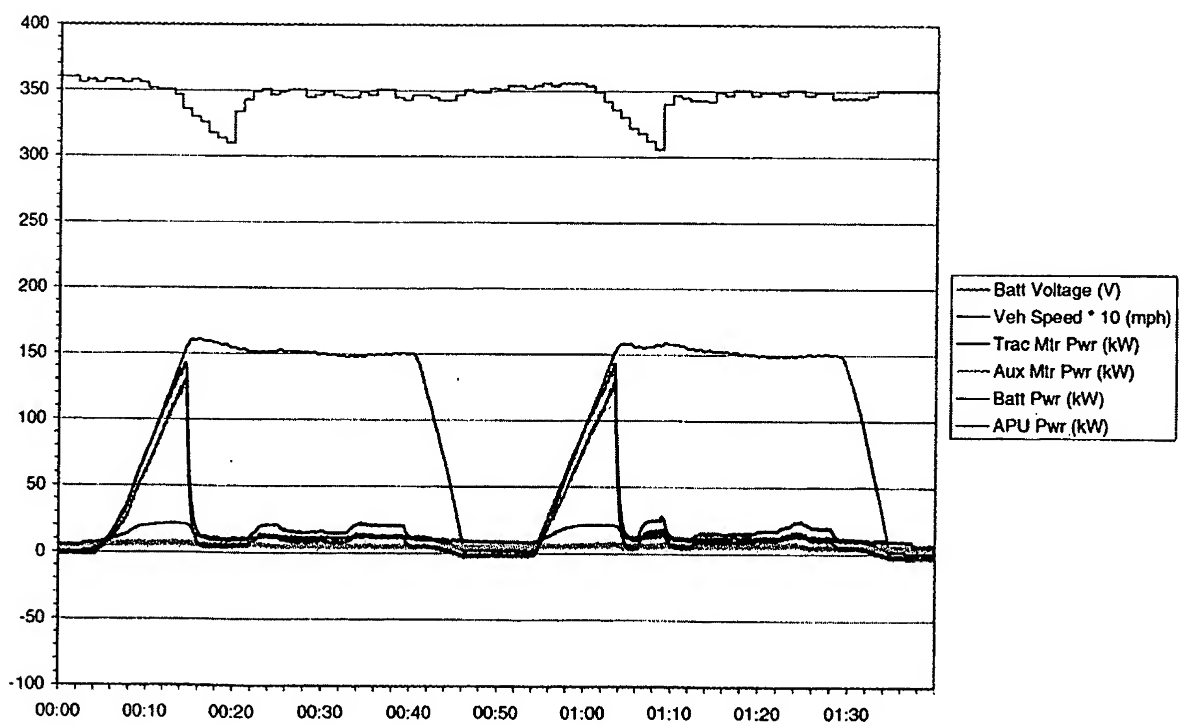

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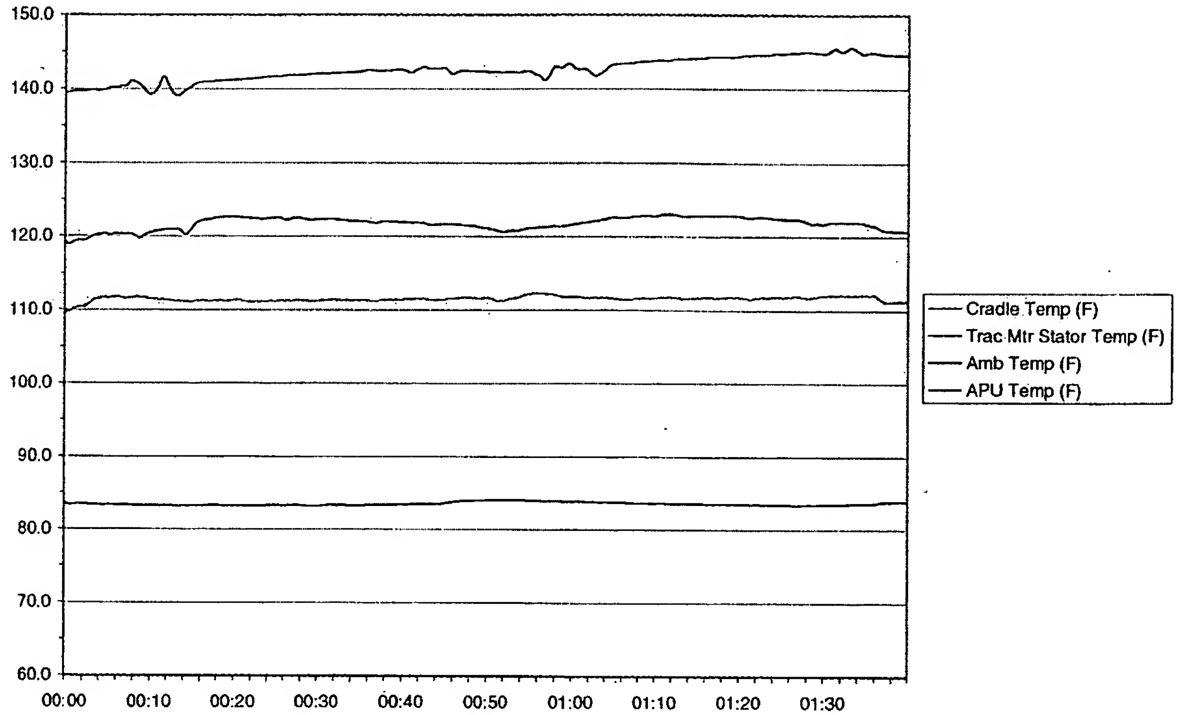


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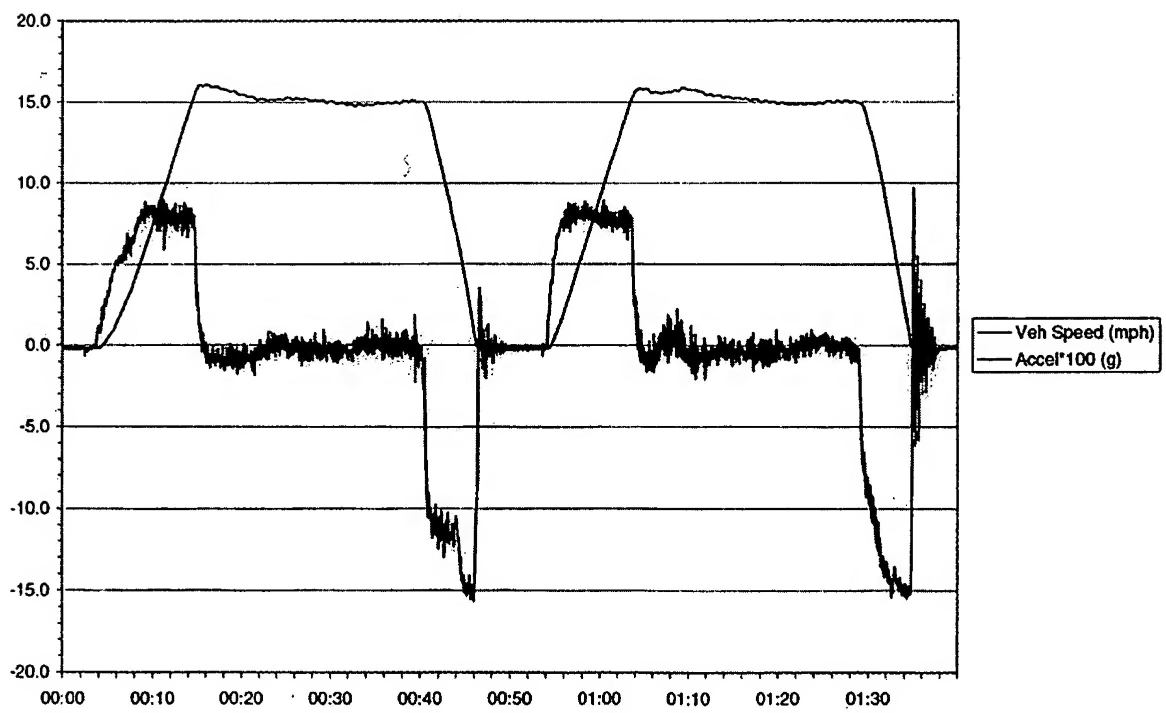

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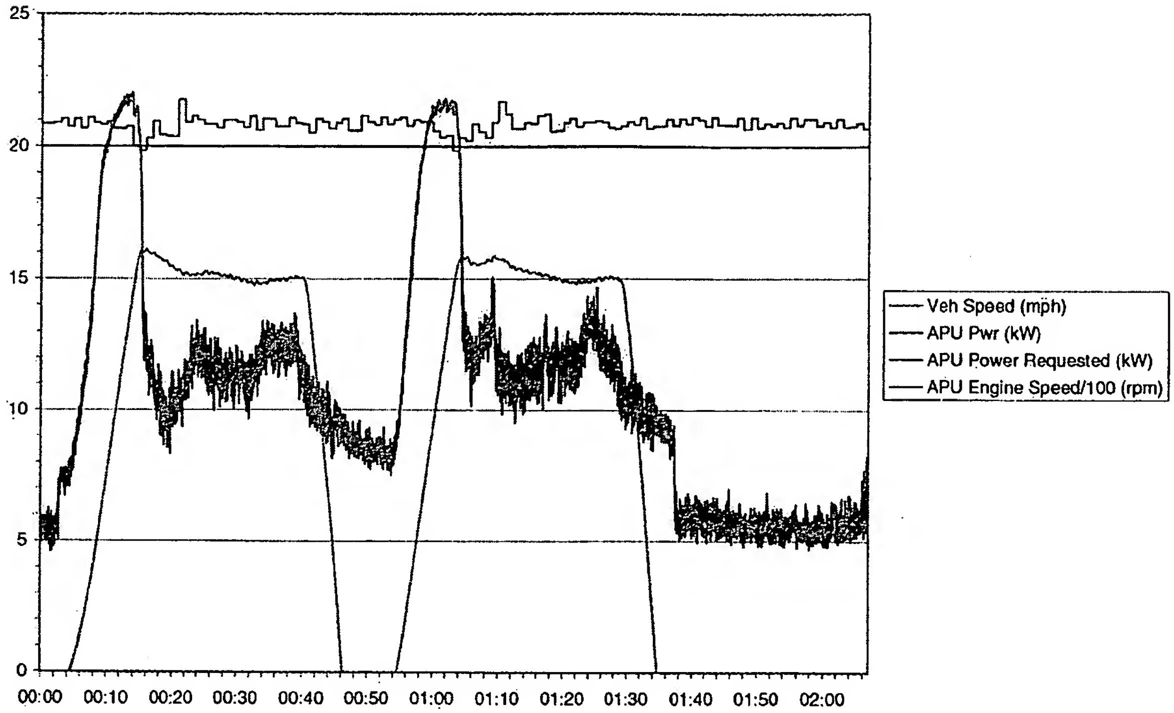


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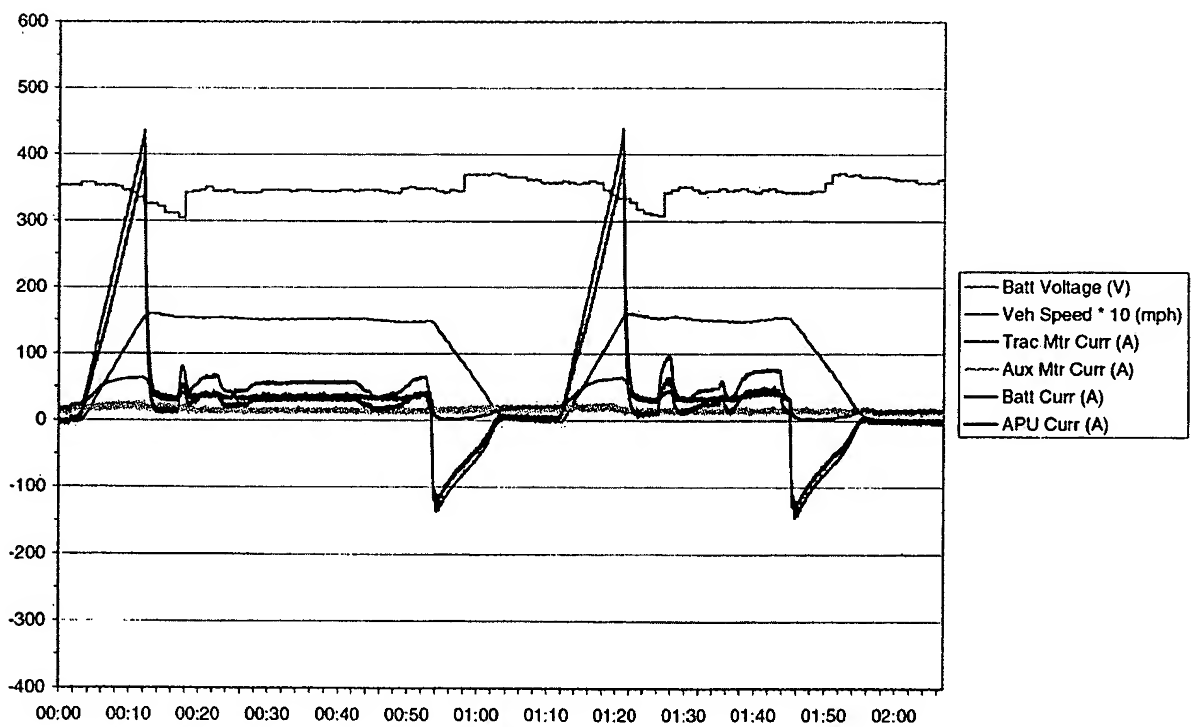

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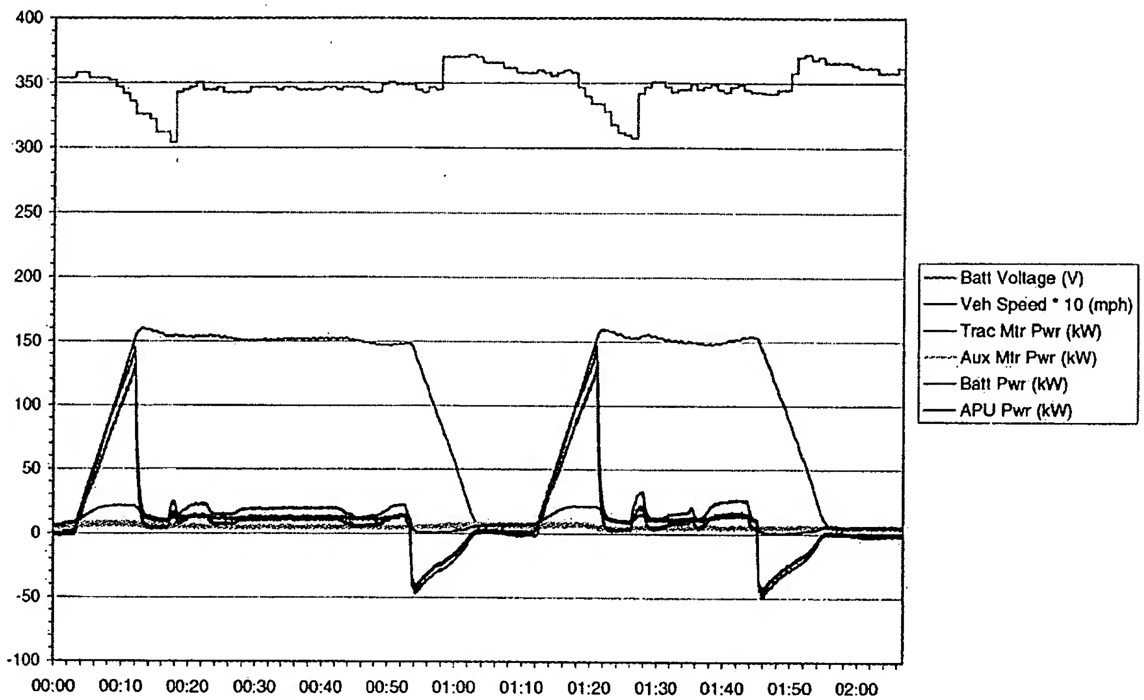


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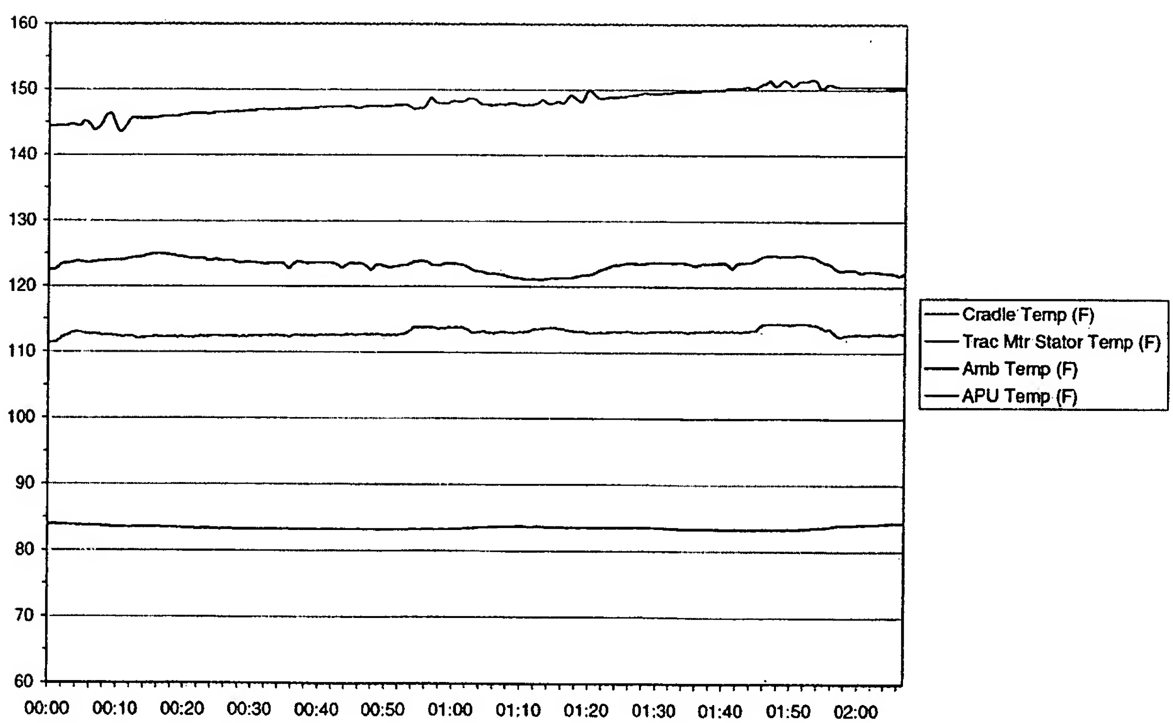

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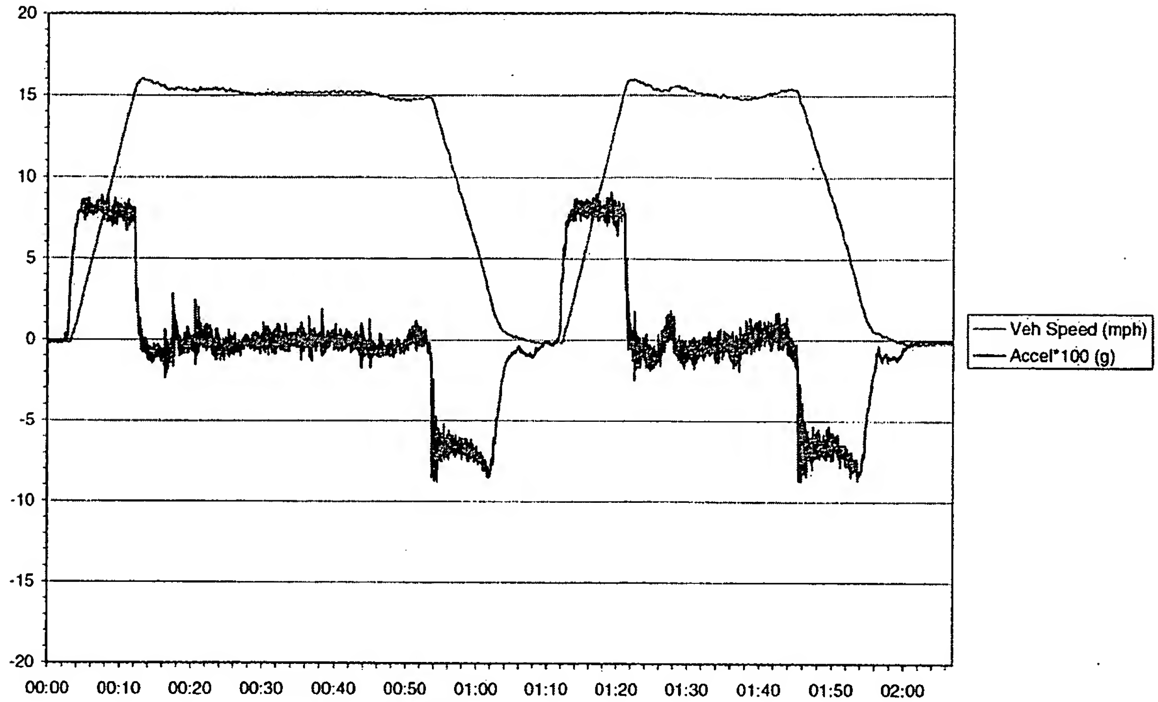


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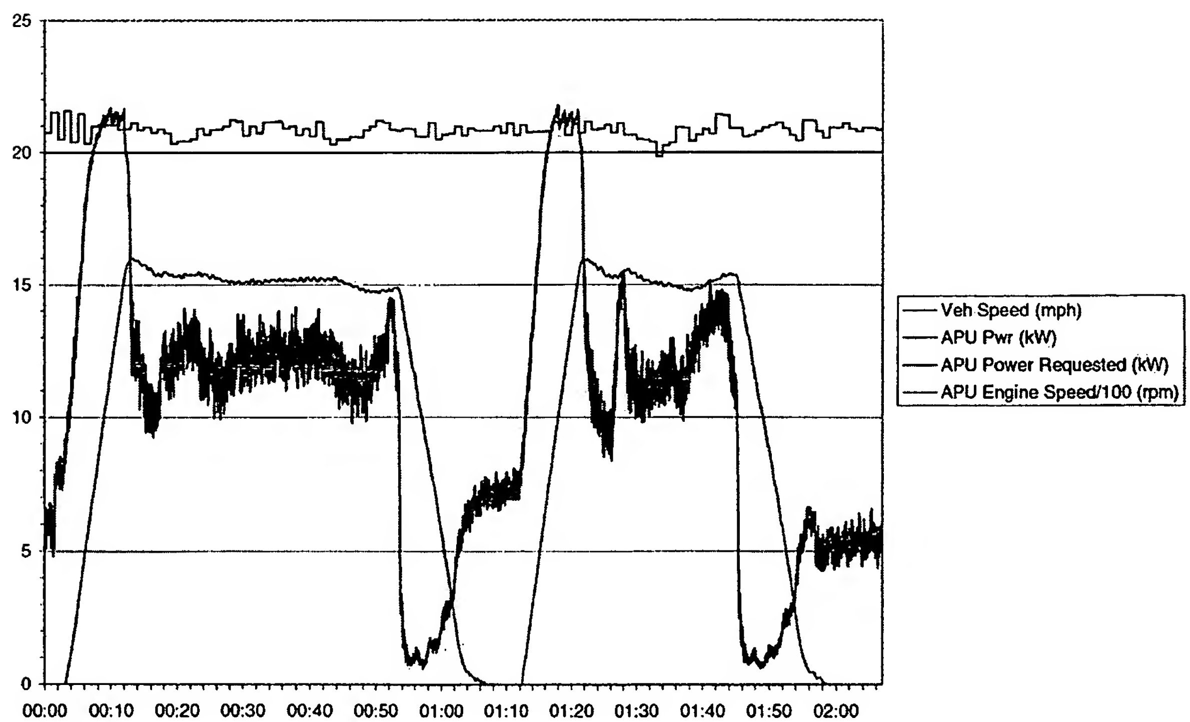

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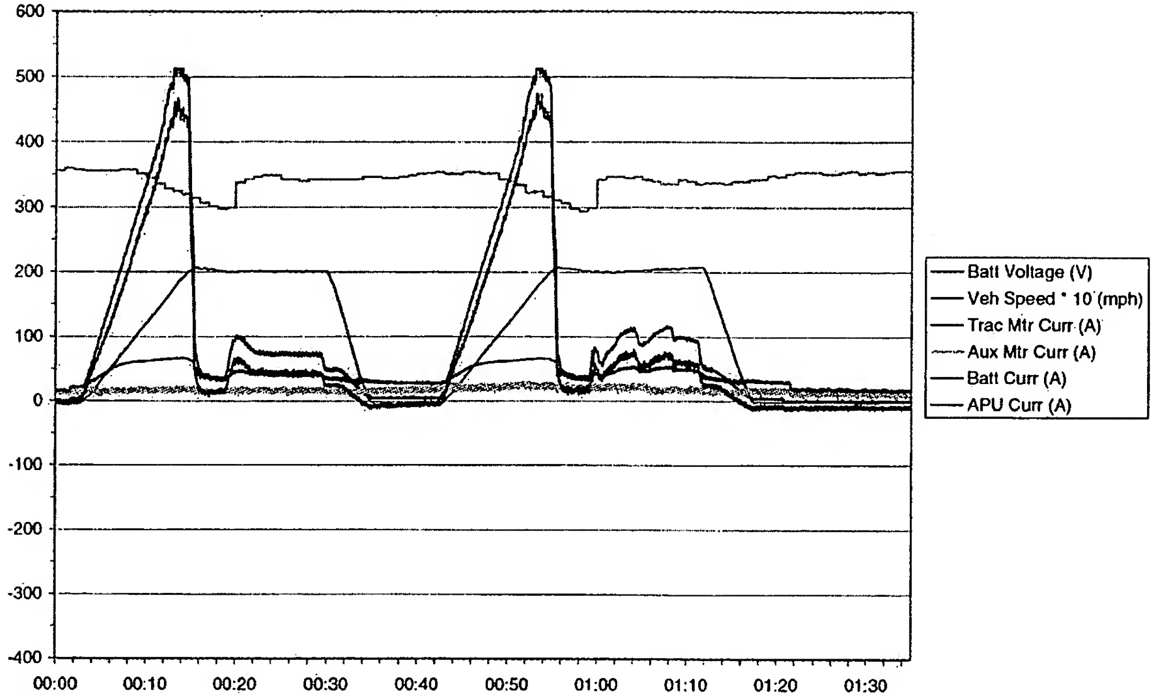


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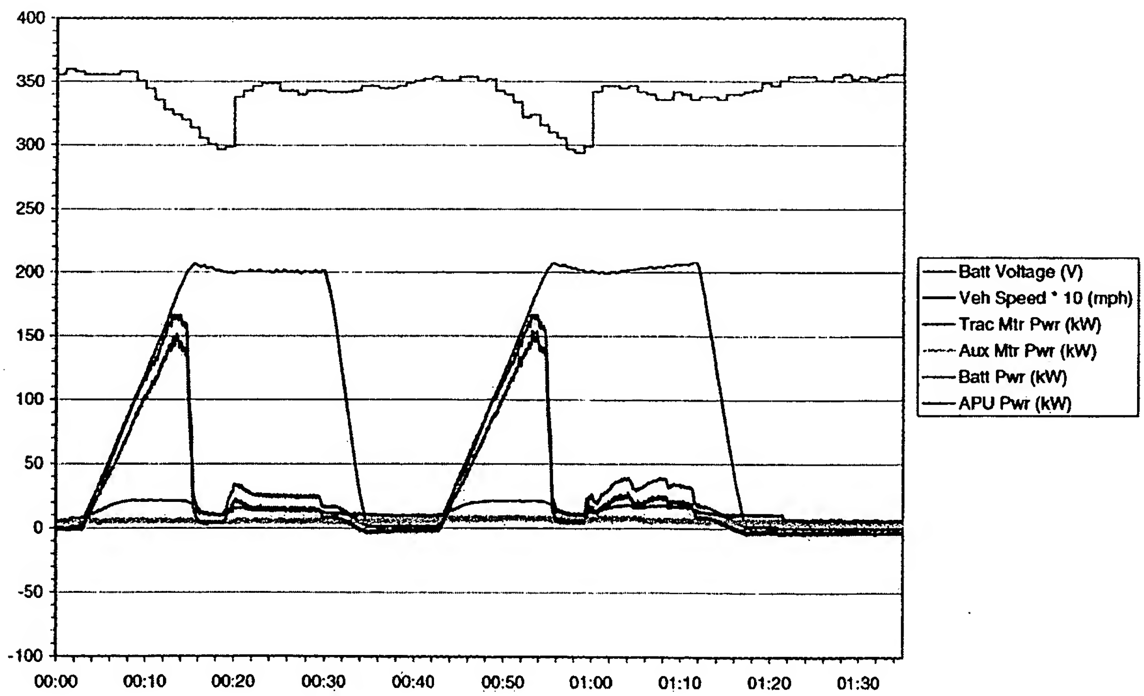

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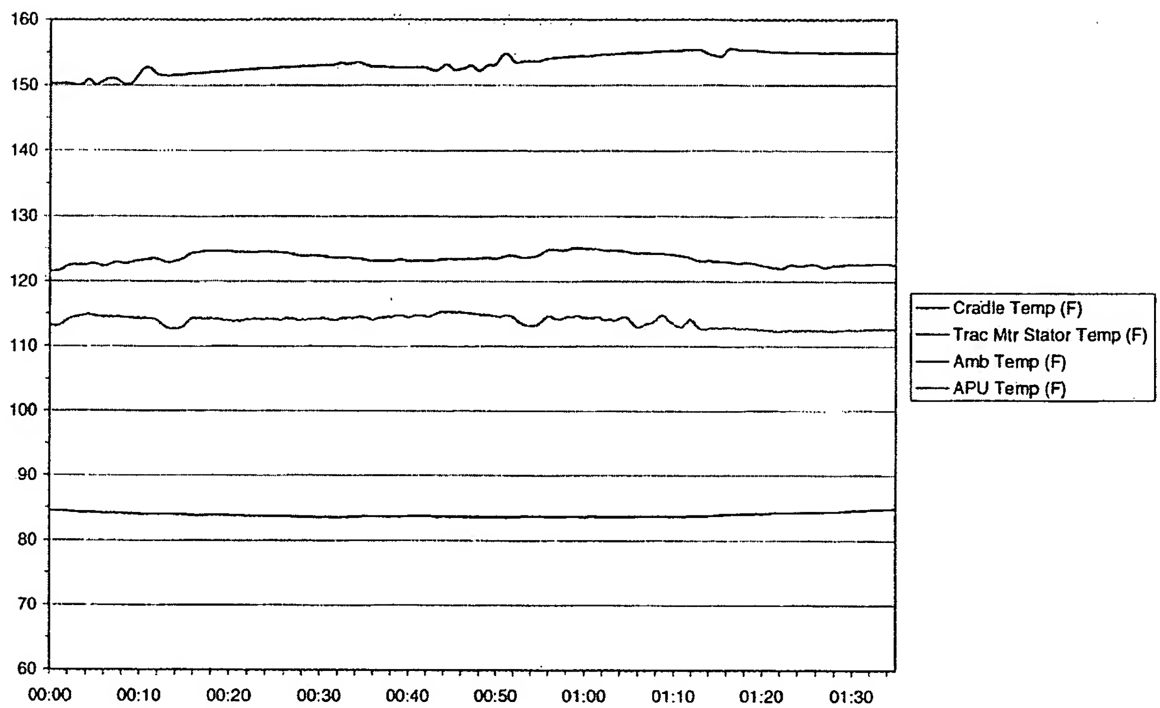


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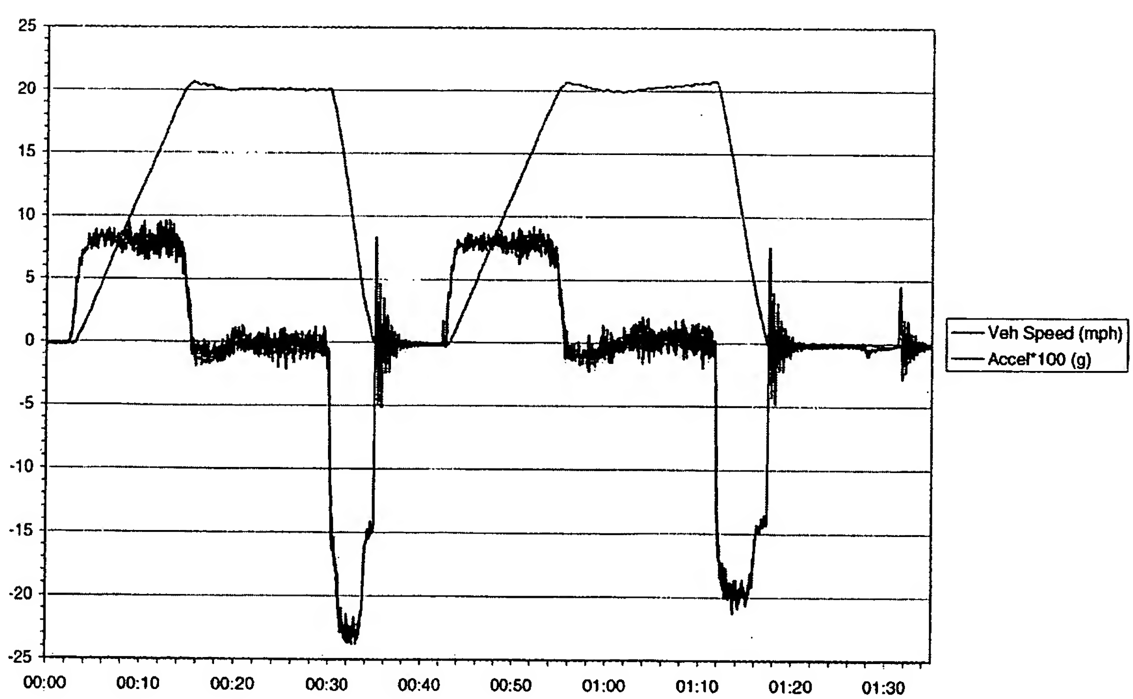

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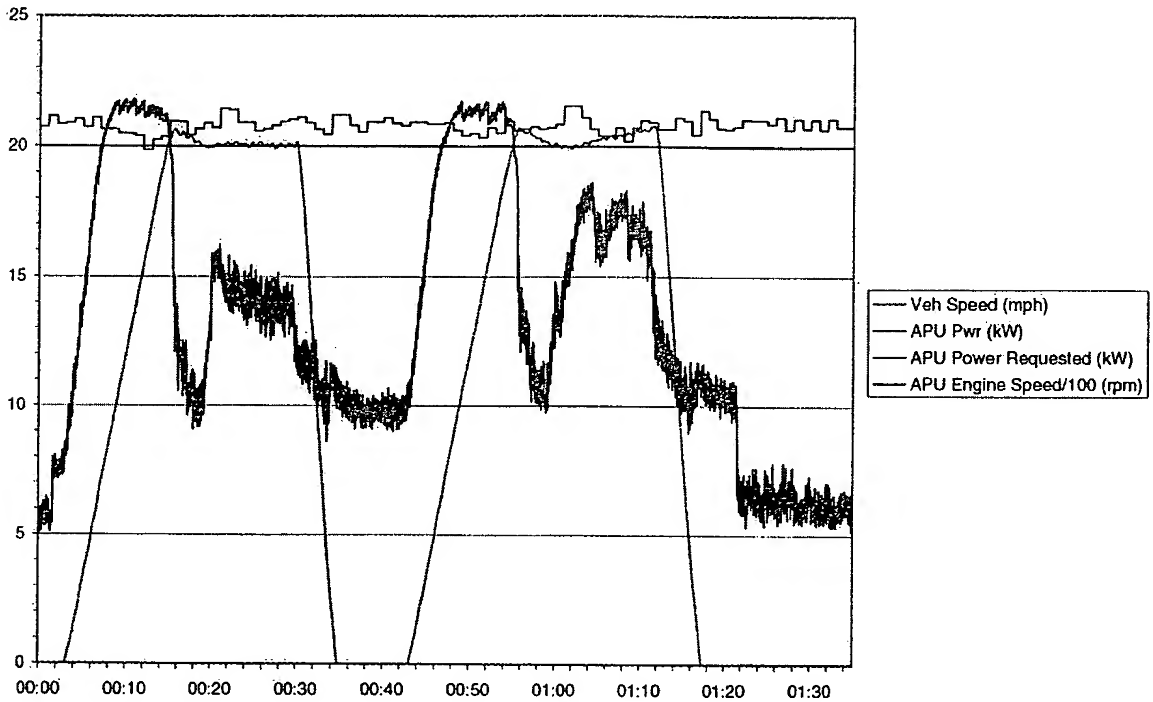


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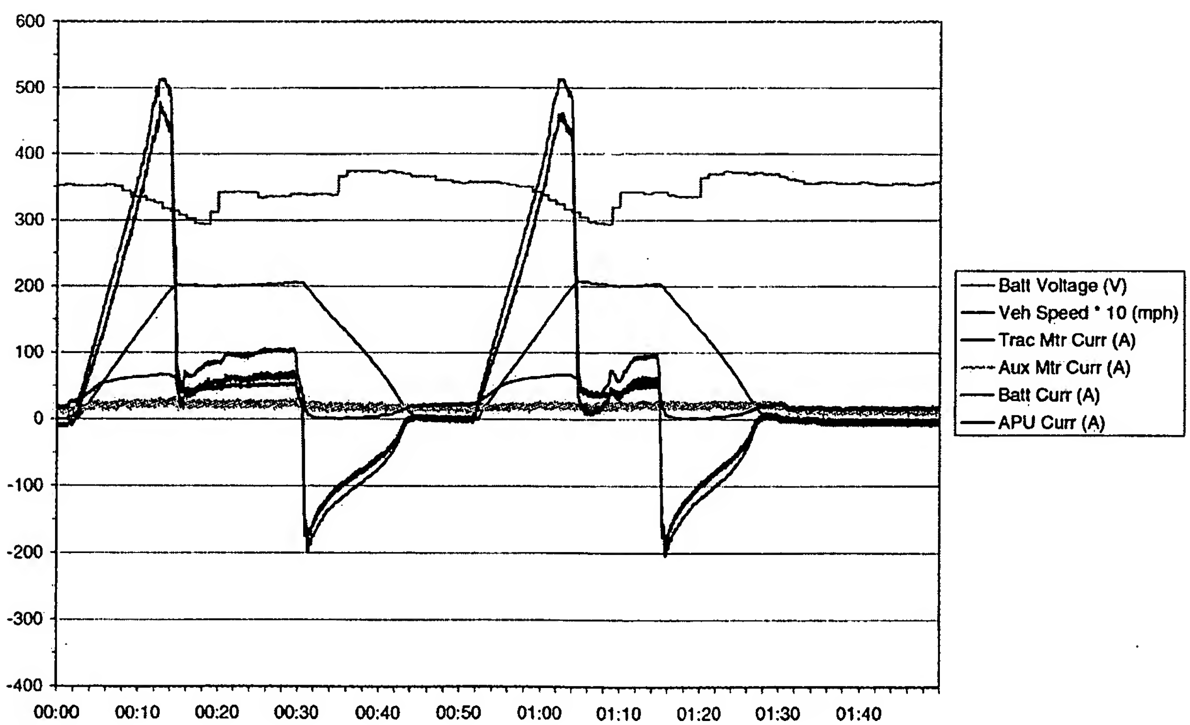

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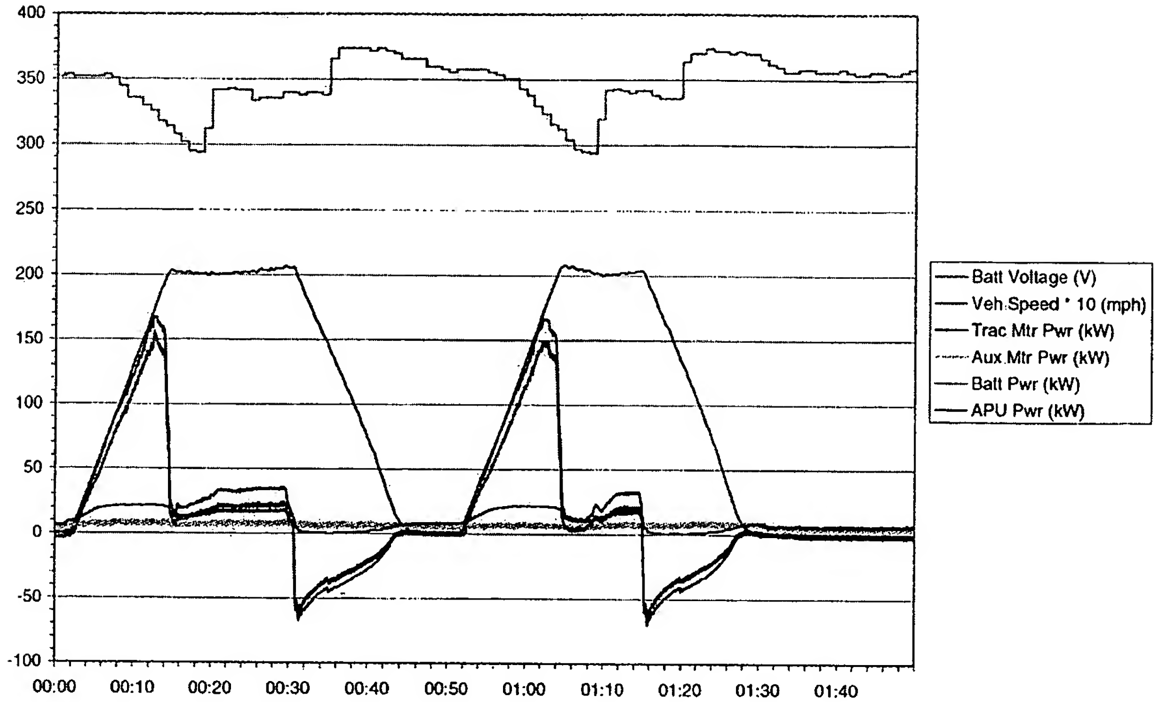


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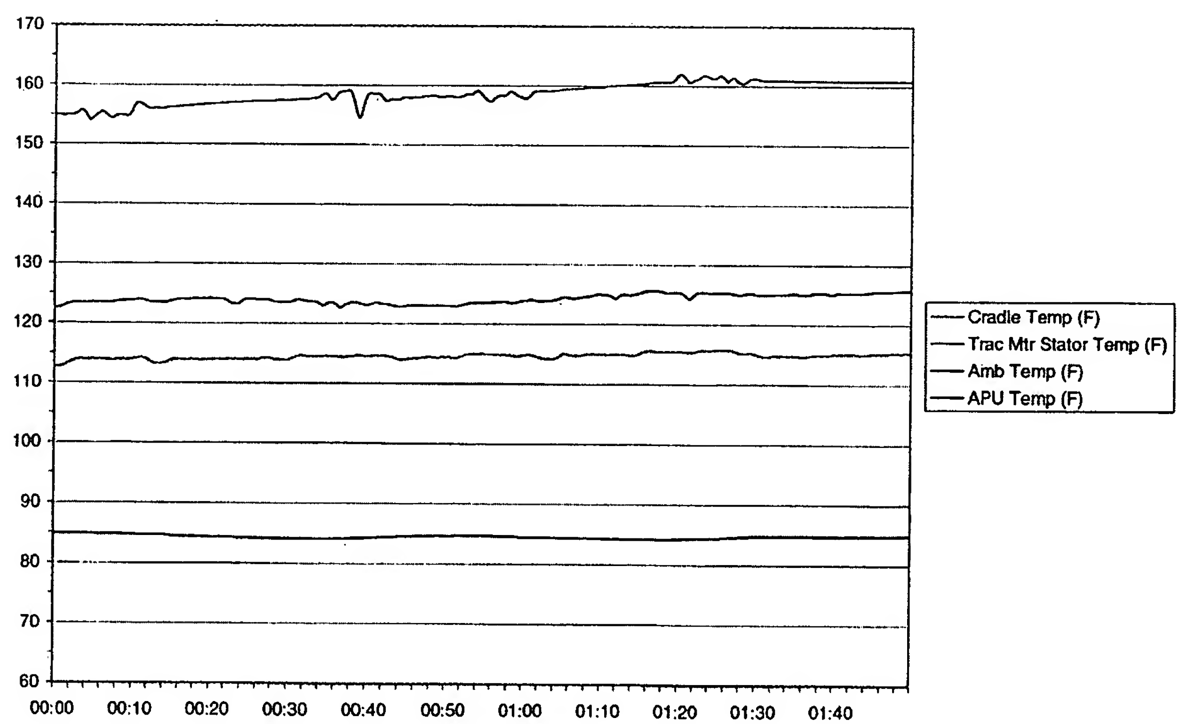

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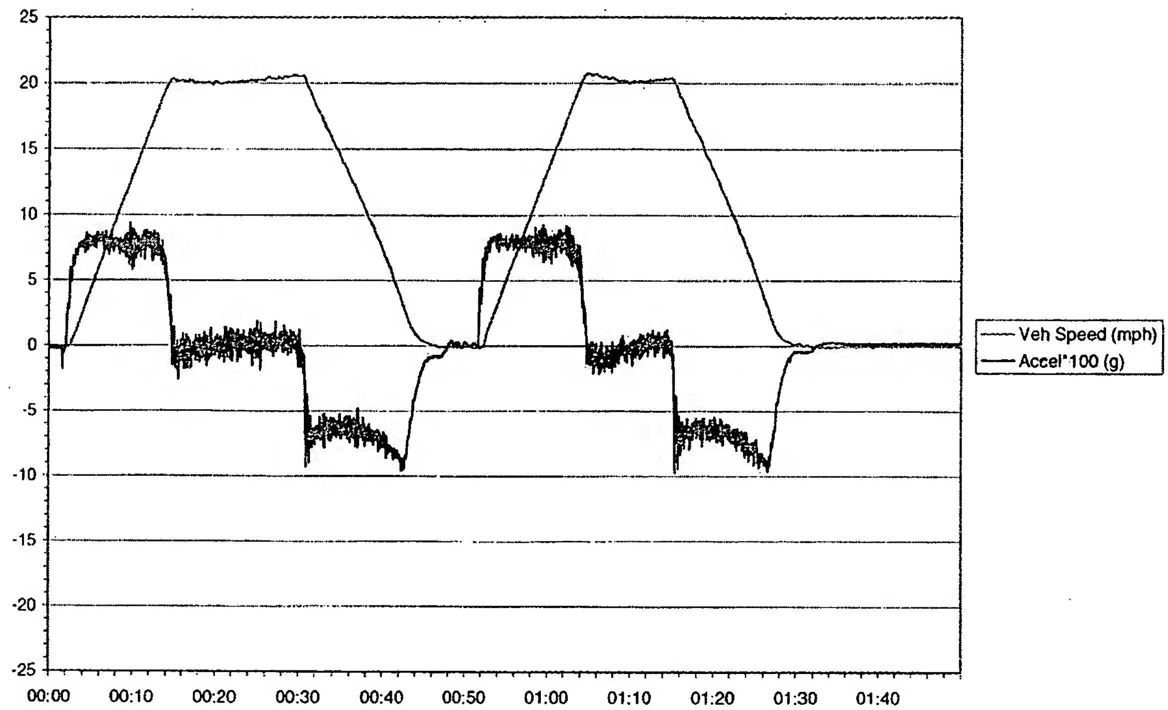


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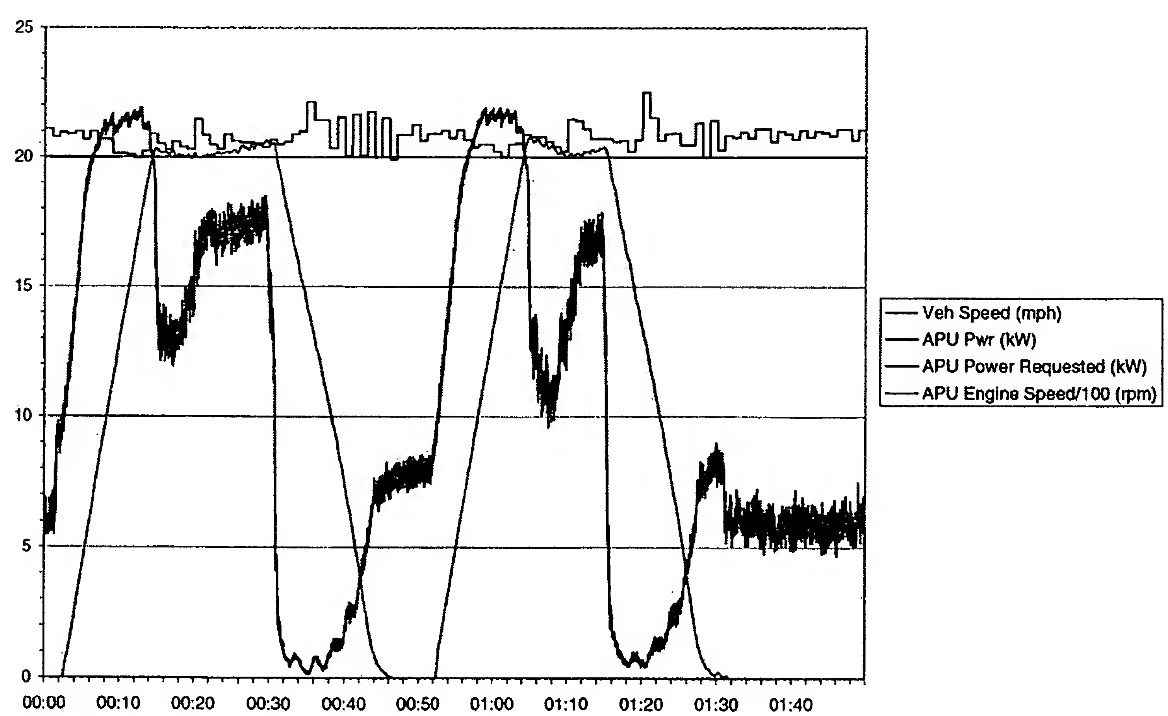

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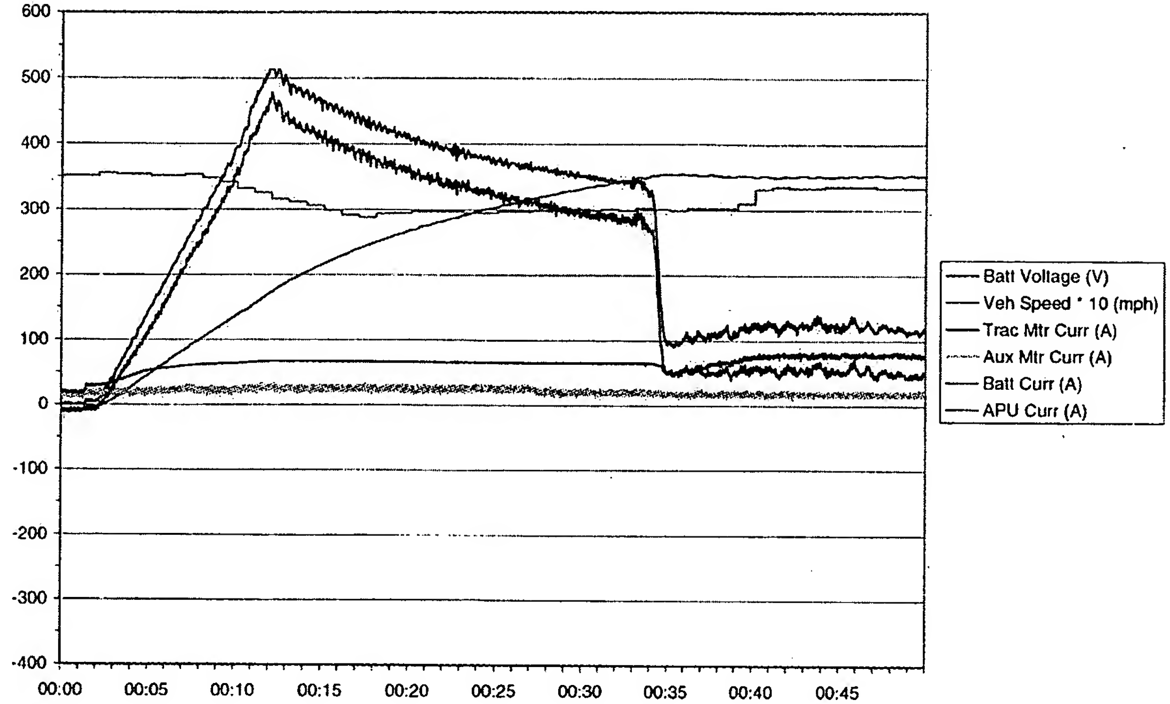


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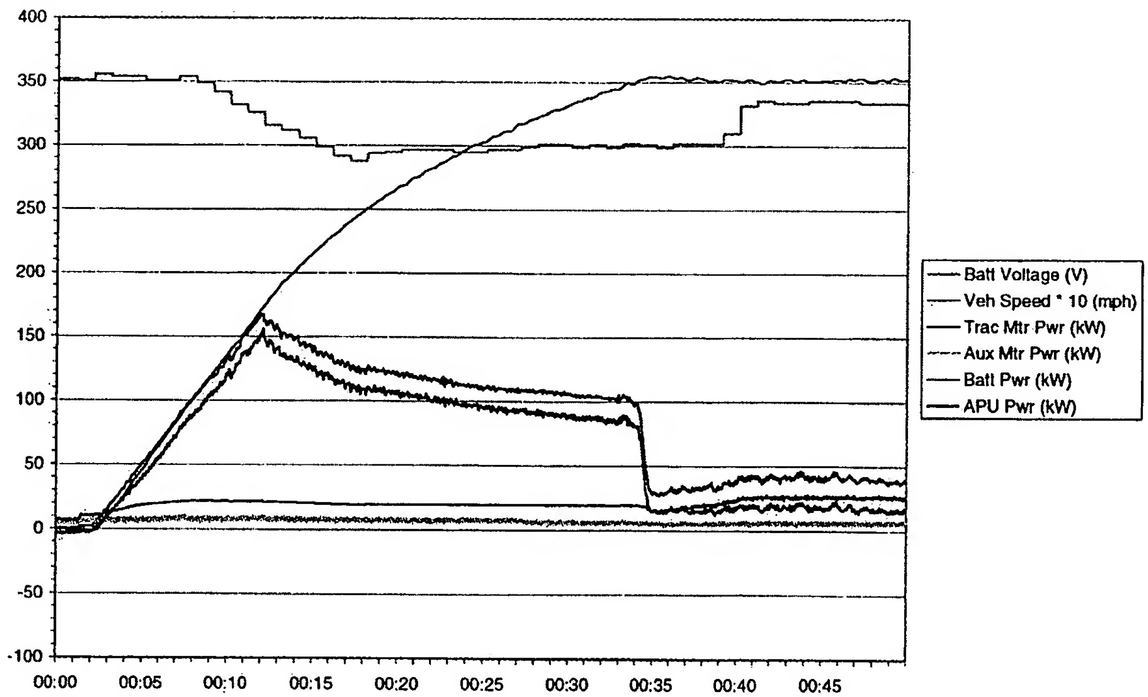

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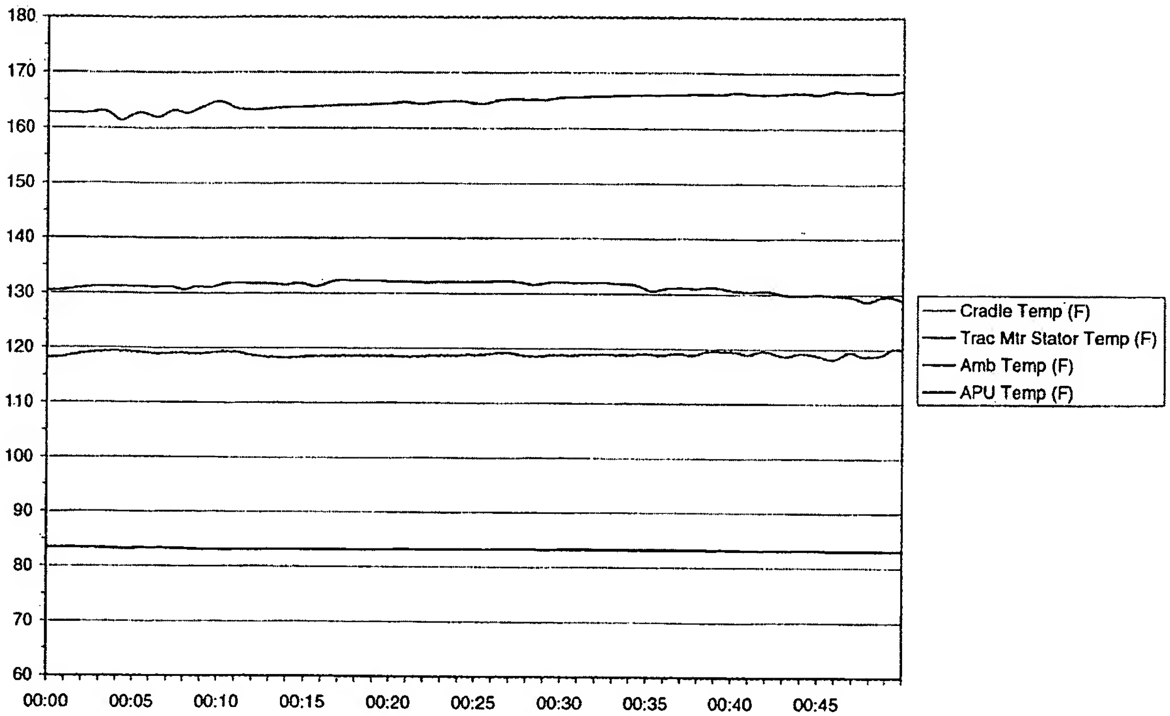


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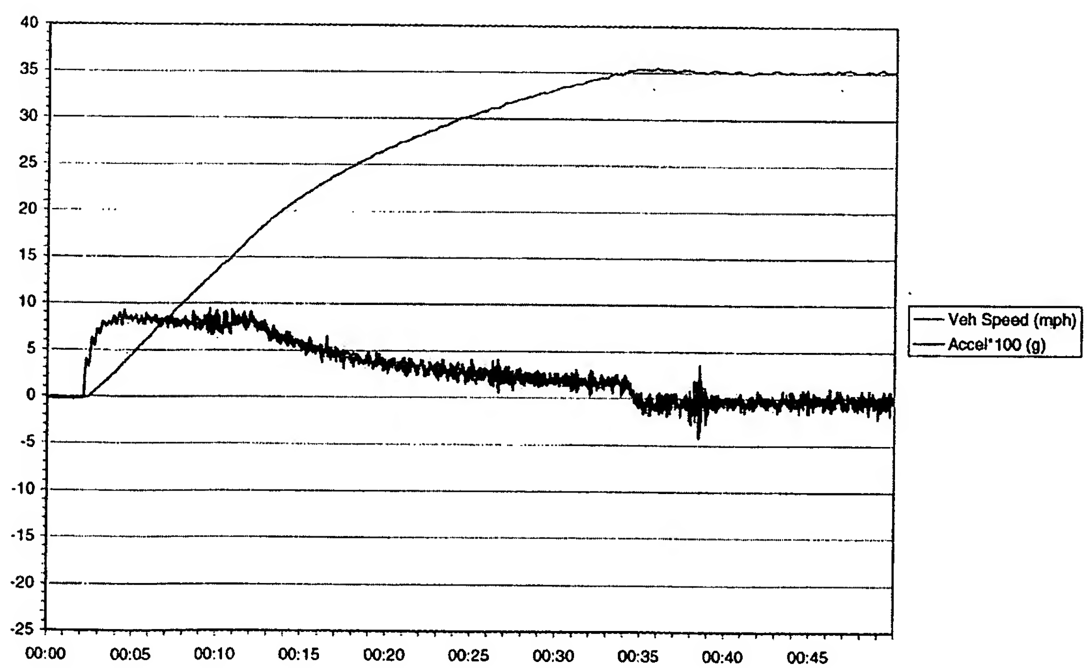

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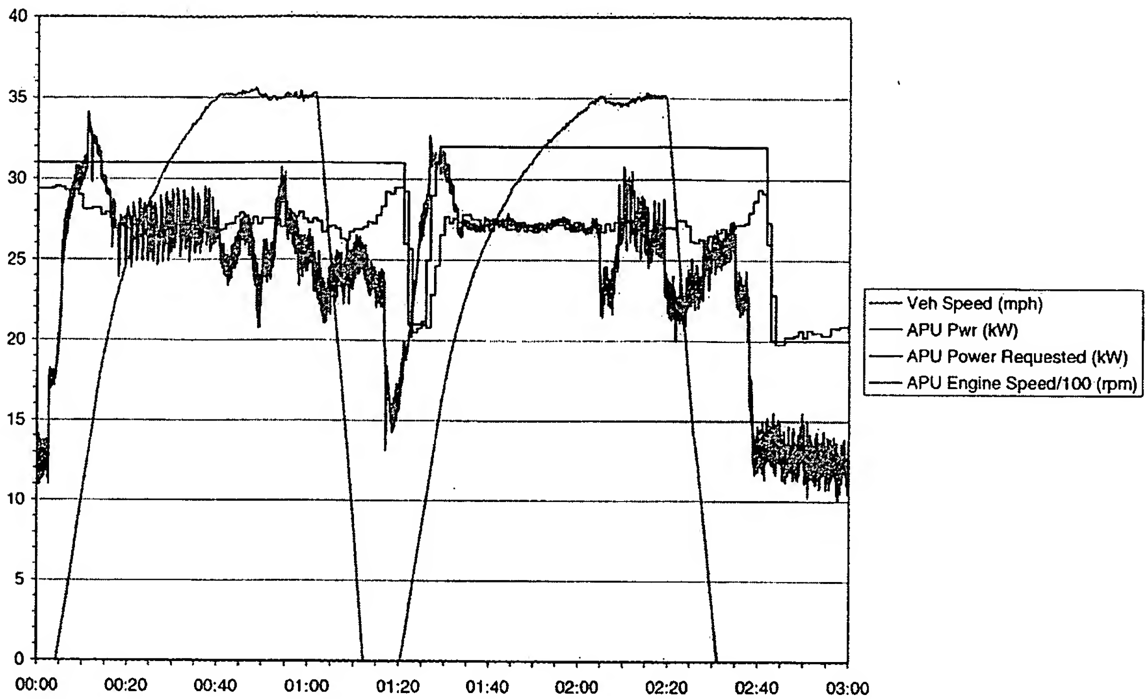


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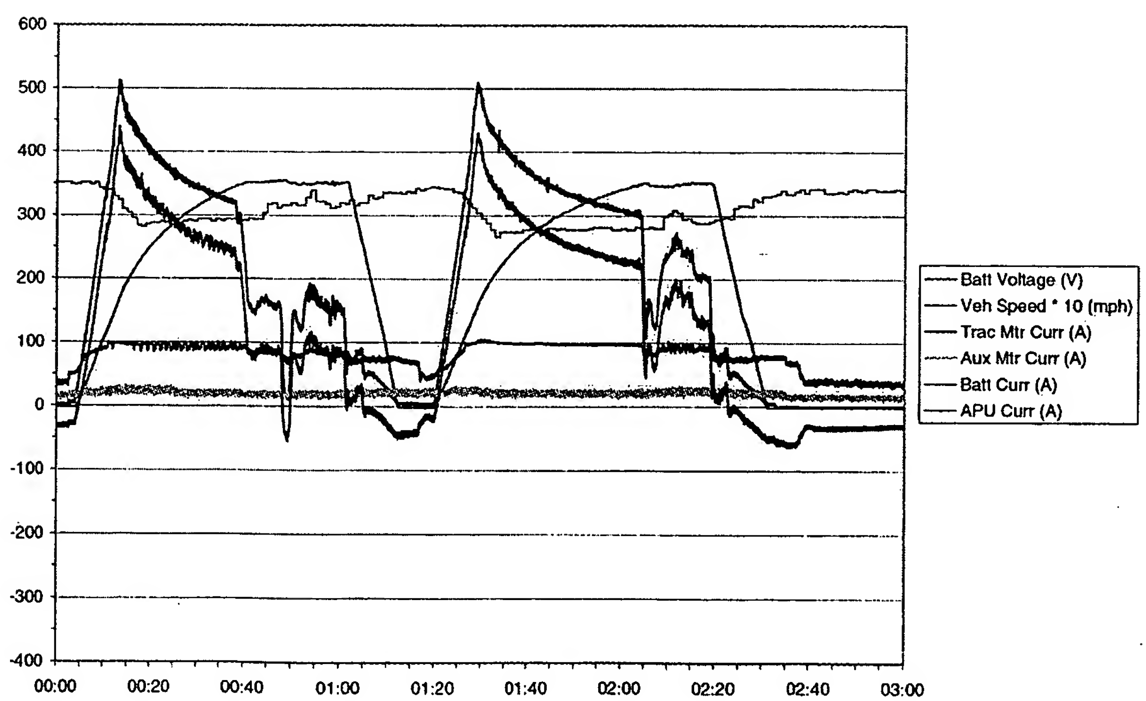

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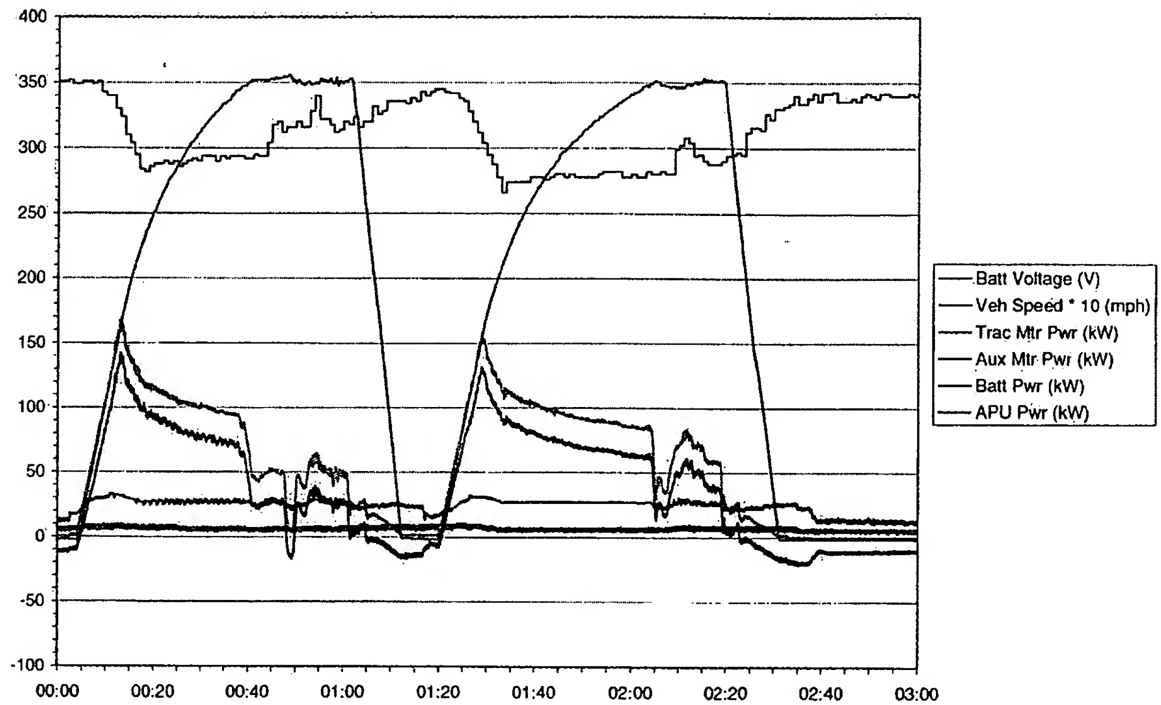


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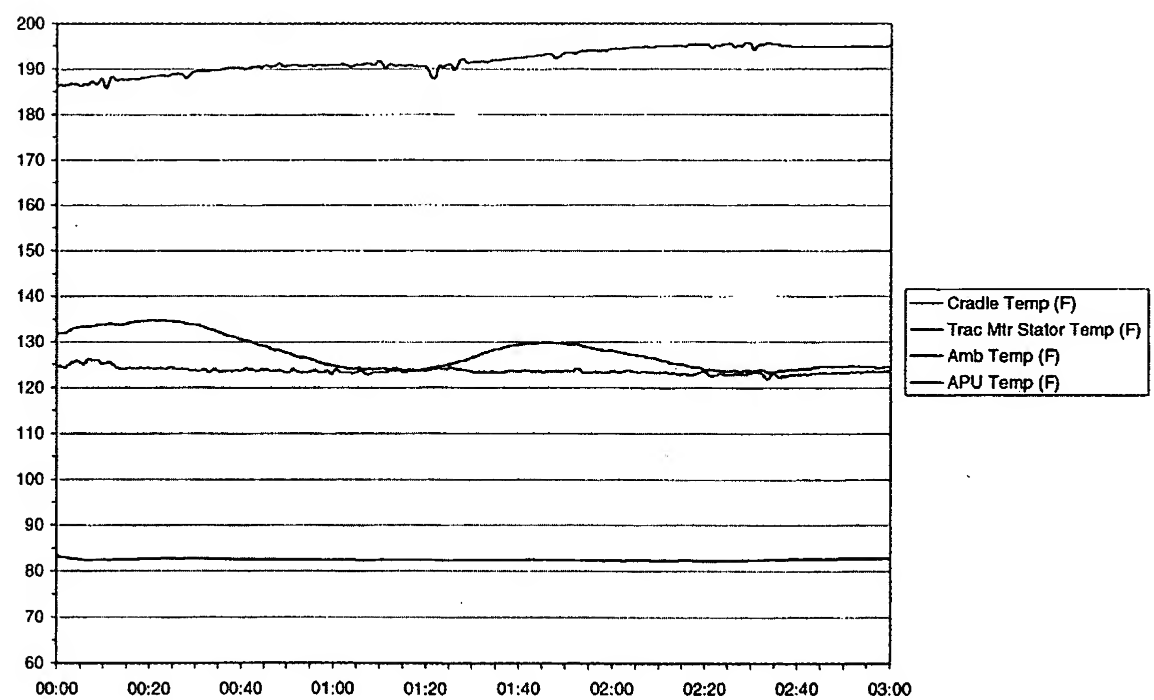

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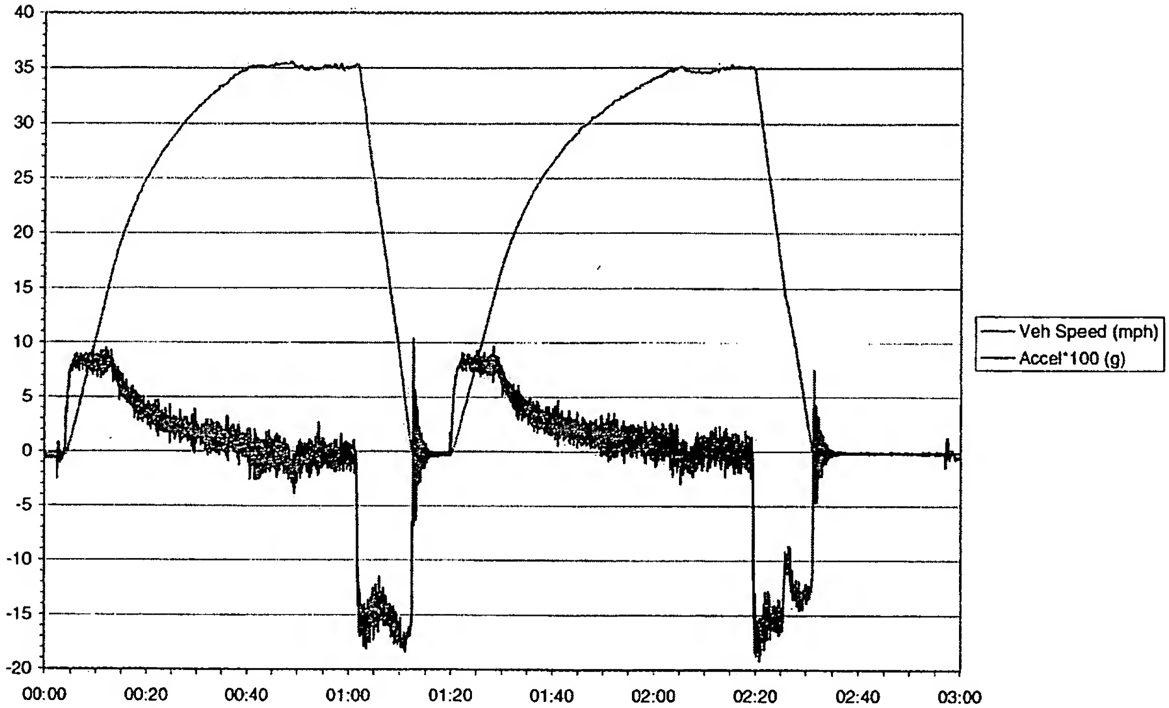


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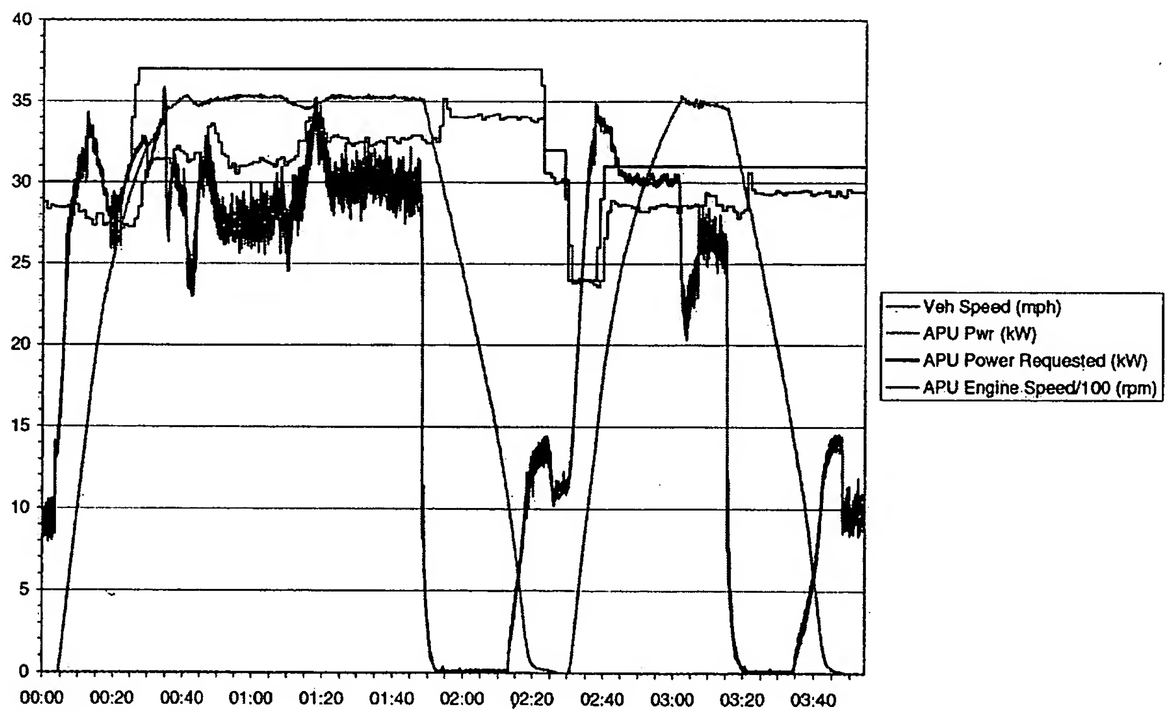

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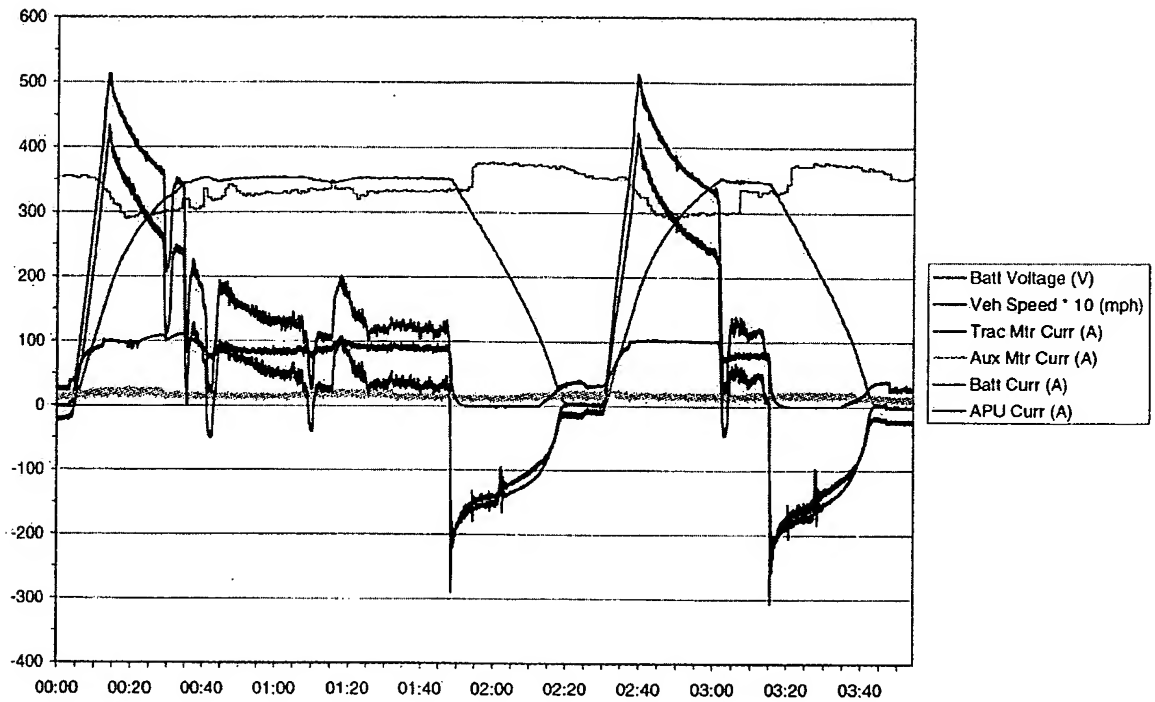


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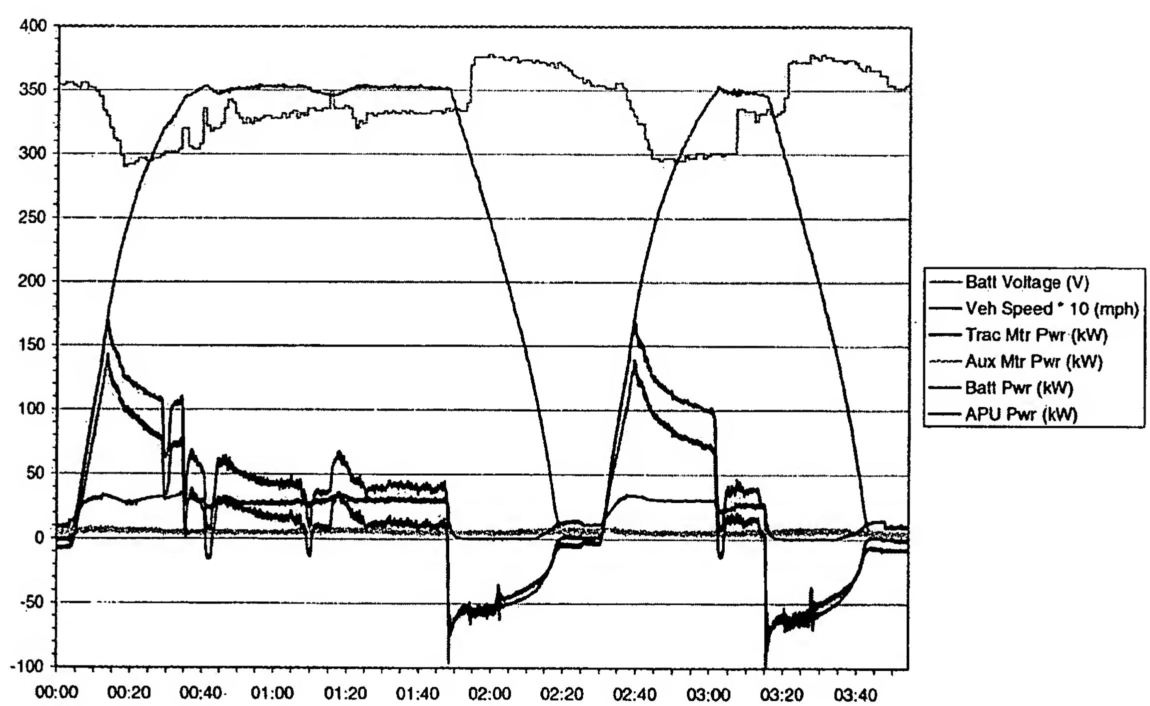

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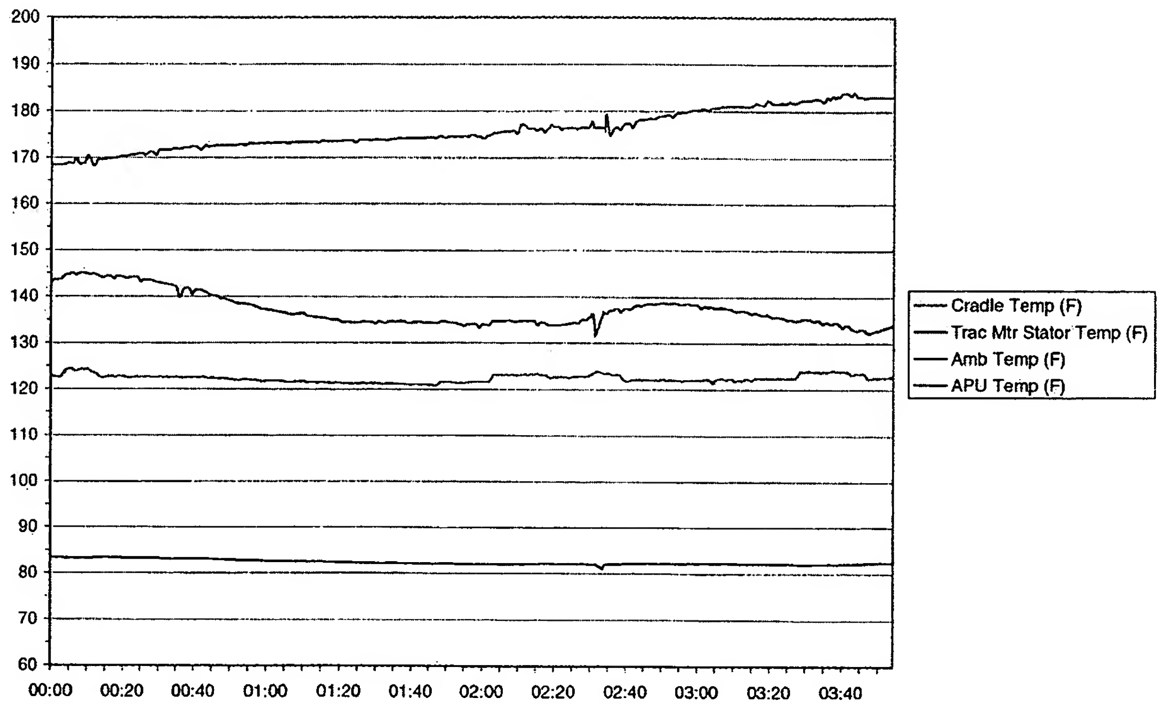


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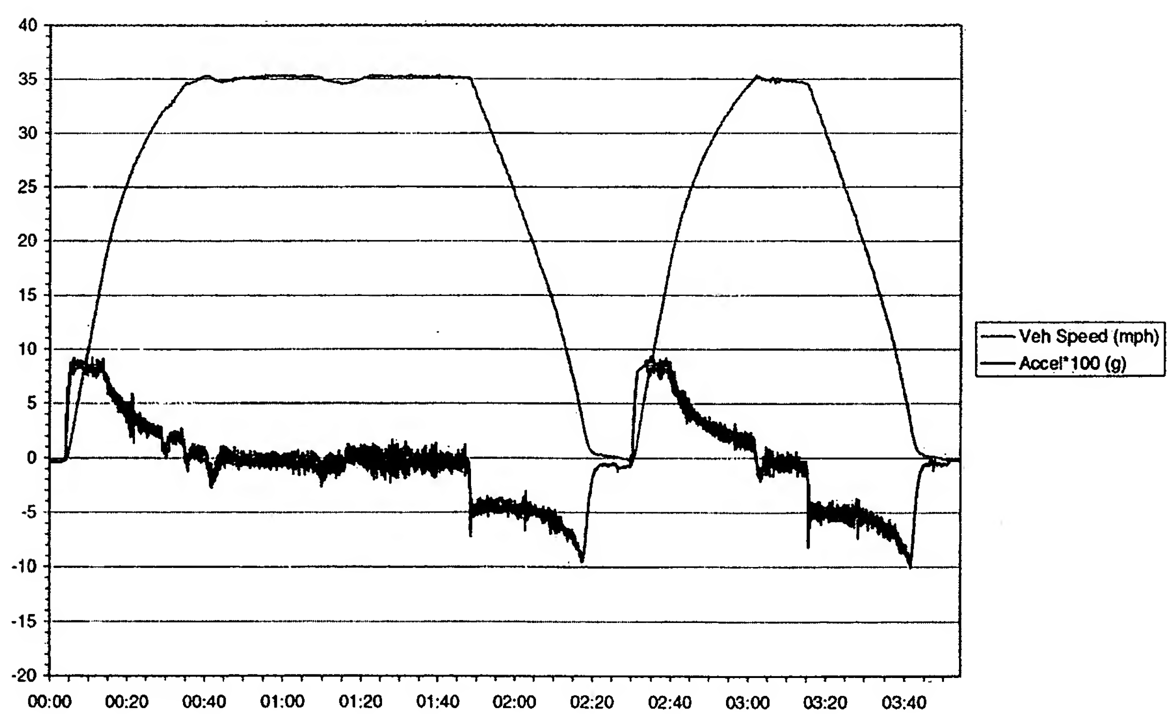

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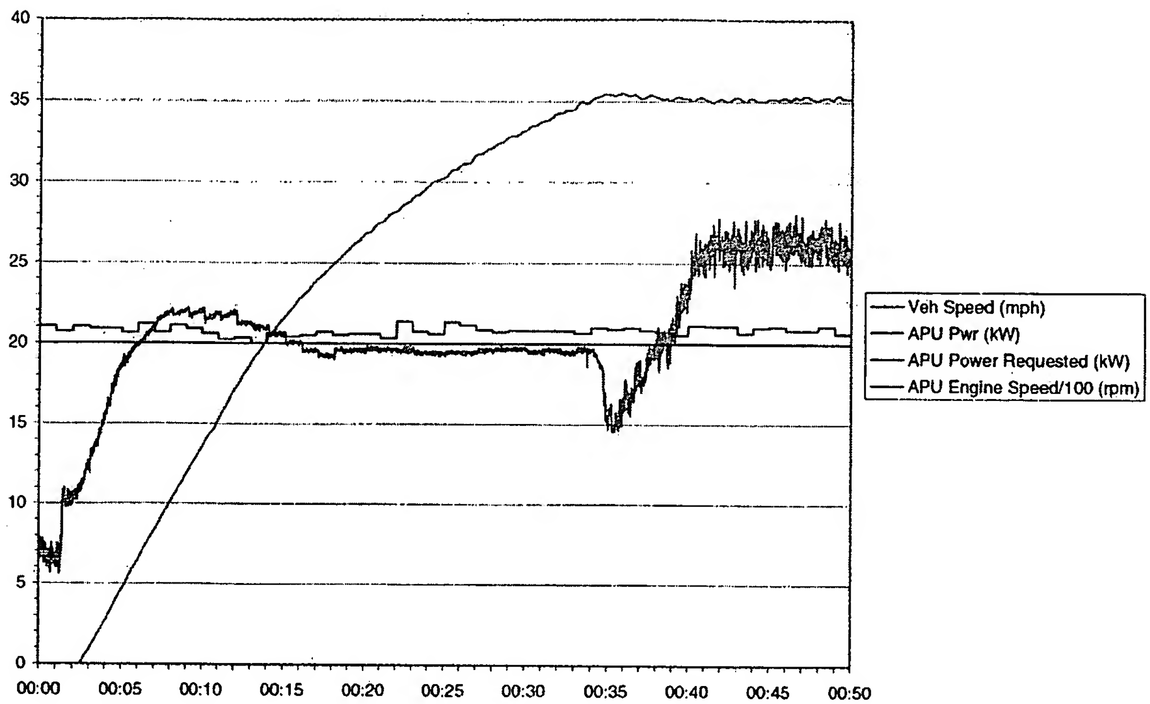

APPENDIX F

# DESCRIPTION OF CONTROL ALGORITHM FOR THE CAPACITOR ENERGY STORAGE SYSTEM

The capacitor energy storage system is controlled using proportional-integral (PI) control. The capacitor voltage is the control variable. It is acquired once per second from the APU by the laptop PC. The output variable is the APU power requested. The laptop and APU controller communicate via a controller area network (CAN) interface.

## Basic Control Algorithm

At time t=k,

1. Acquire capacitor voltage, $V_{cap}(k)$, from the APU.
2. Calculate the normalized error at time k, e(k), by comparing the capacitor voltage to the desired setpoint voltage, $V_{sp}$. That is, $e(k) = (V_{sp} - V_{cap}) / V_{max}$, where $V_{max}$ is the maximum full scale system voltage, taken to be 400 V. The normalized error is also saved as e(k-1) for the next calculation. The setpoint used for testing was 325 V.
3. Compute the output variable at time k, P(K), with PI compensation, with the equation $P(k) = bP(k-1) + K_c [(1+b)/(1+a)] [e(k) - ae(k-1)]$, where $K_c$ is the controller gain, a is the reset time coefficient ($0 < a < 1$) and b is the integration constant (b = 0 or 1). The values used during the testing were $K_c$ = 1.5 kW/V, a = 0.95123 and b =1. These parameters were determined from the response characteristics of the APU and the sampling rate of 1 Hz. The output variable is saved for use as P(k-1) in the next calculation.
4. Limit P(k) between 0 and the maximum output APU power, which is 39 kW, and submit the power request to the APU via CAN.
5. Repeat steps 1-4 for time T = k+1, k+2, etc.

## Enhancements to the Basic Control Algorithm

Automatic control mode uses the algorithm described above. Manual control mode allows the user to input an APU power setpoint directly. In order to provide “bumpless” transfer between modes, the following steps are taken.

When transitioning from manual to automatic mode, the past value of the output variable, P(k-1), is set to the current value of the manual mode power setpoint. The past error value, e(k-1), is set to 0. The controller setpoint value, $V_{sp}$, is set to the current value of the capacitor voltage.

When transitioning from automatic to manual mode, the last value of the output variable, P(k), is used as the initial value of the manual mode APU power setpoint.

Two additions to the basic control algorithm were made in order to optimize the operation of the APU. Engines run most efficiently when run at constant speed, especially near their “sweet spot”. Quantization and peak holding are two ways of

minimizing the number of changes in APU power requested, and, therefore, the changes in rpm.

Quantization forces the output to assume one of a discrete set of equally spaced output values rather than providing for a continuum of possible output values. The number of quantization levels, n, becomes another system parameter. The effect on the system is to eliminate minor fluctuations in engine speed. A value of n = 20 was used during the capacitor tests described in this report.

Peak holding introduces a delay between the determination of the need for a decrease in APU power and its actual implementation by a time, T. Increases in power are not delayed and they supersede any pending decreases, i.e., increases in power reset the counter used to implement the delay for decreases in power. This provides more nearly constant APU operation during busy start/stop cycles without affecting acceleration performance. Peak holding was not used during the tests described in this report. A typical value for T would be 5 sec.

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**13. ABSTRACT** ***(Maximum 200 words)***

A government, industry and academic cooperative has developed a Hybrid Electric Transit Bus (HETB). Goals of the program include doubling the fuel economy of city transit buses currently in service, and reducing emissions to one-tenth of EPA standards. Unique aspects of the vehicle's power system include the use of ultra-capacitors for the energy storage system and the planned use of a natural gas fueled turbogenerator, to be developed from a small jet engine. At over 17000 kg gross weight, this is the largest vehicle to use ultra-capacitor energy storage. A description of the HETB, the results of performance testing, and future vehicle development plans are the subject of this report.

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